MATHEMATICAL MODELLING AND DEVELOPMENT OF A NON-REFLECTING HYBRID SOLAR COOKER

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CERTIFICATE

It is certified that the work contained in this thesis titled "*Mathematical Modelling and Development of a Non-Reflecting Hybrid Solar Cooker* " by Manish Garg has been carried under my supervision and that this work has not been submitted elsewhere for a degree.

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MANISH GARG

ABSTRACT

A hybrid type solar cooker has been developed with special features to make it user friendly. A mathematical model for the analysis of the performance of solar cookers is presented. The model has been used to predict the performance of the new hybrid solar cooker.

Hybrid solar cookers are a natural extension of the conventional solar cookers which cannot perform under adverse conditions like bad weather. A supplementary source of energy combined with a solar cooker enhances its cooking capability and gives a better choice to the user.

The results obtained from the computations and the experiments are compared and a satisfactory to good agreement is found.

The experimental and the computational investigtion confirmed the validity and success of inclusion of certain new features in the design.

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LIST OF PLATES

NOMENCLATURE

A	Area, m^2
C_p	Specific Heat, J/Kg K
d	Diameter
dT/dt	Rate of Temperature change at the Oven Component, K/S
h	Height, m; Heat Transfer Coefficient, W/m K
$\overline{Is}$	Total Solar Radiation on any Component inside the cooker, W/m^2
k	Conductivity of the component, W/m K
F_{ir}	View Factor for Heat Transfer from the Surface i to Surface r
I_g	Global Radiation Intensity, W/m^2
I_d	Diffuser Radiation Intensity, W/m^2
I_b	Beam Radiation Intensity, W/m^2
I_t	Total Radiation Intensity, W/m^2
R_t	Tilt Factor for Beam Radiation
R_r	Tilt Factor for Reflected Radiation
R_d	Tilt Factor for Diffuser Radiation
T_t	Total Radiation on the Titled Plane
T_n	Radiation Transmitted into the Cooker, W/m^2
M	Mass, Kg
Q	Heat flux, W
T	Temperature, K

Greek Letters

α	Absorbivity
Δt	Time Step, sec
η	Efficiency
ϵ	Emmissivity
σ	Stefan-Boltzman Constant
τ	Transimitivity

Subscripts

a	Air
al	Aluminium

b	Back
comp	Component
c	Convection
cd	Conduction
cr	Convection and radiation combined
ct	Contact
d	Down
f	Front
i	ith Surface
l	Left
p	Bottom Plate
r	Right, Radiation, rth Surface
Sp	Side Plate
u	Up
V	Vessel
v-1	Vessel size 1
v-2	Vessel size 2
vb	Vessel Base
vc	Vessel cover
vs	Vessel Side
w	Water
1	Vessel 1
2	Vessel 2
3	Vessel 3
4	Vessel 4

CHAPTER 1

INTRODUCTION

1.1 ENERGY SITUATION:

"Every year the forest moves further and further from house; now I have to walk three hours a day to collect what wood I can." The speaker is an Indian woman from the Pacific Plain Of Guatemala, where clearing for export farming has all eliminated the forest sources of fuel wood. Facing the hard realities of the energy problem are characterized primarily by very low input of commercial energy, large dependence on non-commercial energy.In a vast rural economy like India it is not surprising that the energy consumption has been of non-commercial fuels. With increasing urbanisation and industrialisation the changes towards a larger use of commercial fuel are not only imminent but already visible [53], as seen in the table below :

TABLE 1.1

Source of Energy	1953-54	60-61	65-66	70-71	75-76	80-81
Commercial Energy	32	41	48	53	56	58
Non-Conventional Energy	68	[illegible]	52	47	44	42

India's use of energy is reflected in the diversity of

the country itself. With rural India composing a majority of the population, it is but natural that even 40 per cent of the total energy consumption consists of fuel wood, crop residue and animal dung. It is difficult in fact to compute the real amount; the figures are basically those which are calculated after the commercial energy consumption are known.Energy consumed by urban population is found to be around five times to that of the rural masses resulting in poor living conditions. Scarcity of capital for investment on technologies employ more efficient utilization of available energy resources. All these factors have contributed to the pitifully low consumption of energy per capita and consequent low productive output.

Studies on energy use in developing countries have revealed that cooking and agriculture operation make the heaviest demands on energy budgets and labour time. On the other hand the consumption of conventional energy sources is leading to ecologic and economic crises. They could be alleviated considerably by the widespread use of renewable energy resources.

1.2 RENEWABLE ENERGY:

Solar, wind, tidal, ocean, biomass etc. are the only energy sources which can solve the present and future energy problems. they are available in abundance and are environment friendly. It has been estimated that the rate of tidal energy dissipated for the world is about $3x10^6$ MW. On an average it is estimated that about 10 KW are available for every meter of wave front. The amount of electricity which could be generated from

geothermal dry or wet sources all over the world is estimated to be 62,500 MW for a period of 50 years. The energy available in the winds on the earth's surface is estimated to be 1.8×10^{7} MW. The power from the sun entercepted by the earth is approximately 1.8×10^{11} MW.

1.3 SOLAR ENERGY USE

1.3.1 SOLAR ENERGY:

The source of solar energy is sun, a gaseous star. Itprovides a free , non-polluting and everlasting source of energy. In principle a fraction of the solar energy intercepted by the earth could supply all the present and future energy needs of the world. Considerable research has been carried out to utilize the solar energy for purposes such as water heating, high temperature ovens, conversion to electric energy, etc.

The main disadvantage of solar energy systems has been the low efficiency attained in most of its practical applications. If solar energy were to provide as much energy as was used in the USA in 1975 at a conversion efficiency of 25 percent, solar collectors would have to cover an area equal to the entire state of West Virgina. This amounts to 0.7 percent of the total USA land area. It is expected however, that due to continuous decrease in the availability of other energy sources such as oil and coal, along with the safety problems associated with nuclear energy, man's need for utilization of solar energy will increase, causing leading him to find ways and means to develop adequate and efficient solar-powered systems.

Solar energy can be converted into a useful form by

either an electric, chemical or thermal process.

1.3.2 SOLAR THERMAL ENERGY:

The thermal conversion of solar electromagnetic energy is accomplished by absorbing it in a absorber. The absorbed energy increases the absorber's temperature. This heat then may be used for some other purposes, such as providing heat to a structure or industrial process, or providing heat to a cooling or mechanical system. Some of the applications of solar thermal energy are listed below:

(A) SOLAR WATER HEATING:

It is one of the most attractive applications from an economic stand-point. Solar energy is directly absorbed by an absorber which transfers it to the water to be heated. The heated water is collected in an insulated tank.

(B) SPACE HEATING:

This is of important for colder countries where significant amount of energy is used for this purpose. There are two ways of heating a house. One way is to heat water in the solar collector and then pass it through heat exchanger, rendering hot air to be circulated in the house. In the alternate approach the air to be circulated is directly heated in the collectors.

(C) POWER GENERATION:

The generation of the electrical or mechanical power is one of the most important applications of an energy source . Solar

energy is used to heat the water ranging from 100 ^{0}C to 400 ^{0}C or low boiling organic fluids such as R-113, R-114, R-11, etc. up to about 100°C in a boiler and then it is used in Rankine cycle to generate electric power. At present very low overall efficiencies are being obtained from the plants working on this principal.

(D) SPACE COOLING AND REFRIGERATION:

Absorption refrigeration cycle which requires most of its energy input as heat , is used for the cooling purpose. Several institutions as well as industrial organisations have developed experimental models for demonstration purposes. But it has not been commercialized at tangible limit.

(E) DISTILLATION:

This application is of much importance for remote places where fresh water for medical and other purposes is scarcely available . Water is heated by about 10 ^{0}C to 20 ^{0}C in a solar still and vapours formed are collected in perforated trays.

(F) DRYING:

Solar energy is also used for drying of agricultural products. Proper utilization of this technique can save a huge amount of agricultural products from their spoiling every year.

(G) SOLAR COOKING:

An important domestic application of the solar thermal energy is that of cooking. Vessels containing food are placed in an insulated chamber. One side of which is covered with a glass for the solar radiation to enter the cooking space through .

Vessels and the absorber plate inside the chamber are painted with paint black for better absorption of the solar energy. The food is maintained at the cooking temperature for sufficient amount of time (depending upon the solar intensity, weather condition and the amount & type of food stuff).

1.3.3 PHOTOVOLTAIC CONVERSION:

In photovoltaic conversion, the solar radiation falls on devices called solar cells which converts the sunlight directly into electricity. At present the cost is high and efficiency obtained is very low. But there are indications that if some of the new processes invented are commercialized then there are chances of increasing the efficiency and decreasing the cost by a factor of four or five.

CHAPTER 2

SOLAR COOKING

2.1 COOKING:

A wide variety of foods are prepared by the transfer of heat to agricultural products including cereals, vegetables, dairy products and the like. There are wide verities of cooking techniques, with the most common forms beingboiling, steaming, frying, baking and roasting. It has been roughly estimated that over the world approximately 80 percent of the cooking is done either using the boiling or steaming techniques. Solar cookers developed till now are suitable mostly for boiling and baking type of cooking .

2.2 TYPES OF SOLAR COOKERS:

As in all other solar thermal applications, in solar cooking also, the principle is either to concentrate parallel sun's rays to a focus or to absorb the solar energy in a insulated chamber and transfer it to food to be cooked. Based on the method of solar energy collection for cooking, solar cookers can be classified as:

(1) CONCENTRATING TYPE

(2) HEAT-TRANSFER TYPE

(3) HOT-BOX TYPE

(4) HYBRID SOLAR COOKER (A NEW DEVELOPMENT AT IIT KANPUR)

2.2.1 CONCENTRATING TYPE OF SOLAR COOKER:

In this type of solar cooker (fig. 2.1) solar radiation is concentrated by a paraboloid reflecting surface on the cooking vessel which is placed at the focus of the paraboloid reflector. The cooking vessel is thus open to the ambient. Therefore the performance of this type of cooker depends on the *wind speed.* Further, as continuous tracking is required, user has to spend much of his time in the sun. Another disadvantage of this type of cooker is that the reflectivity of all the surfaces except glass deteriorates with time. Despite all these limitations, the achievement of very high temperatures of the order of 200^0 C are reported, being sufficient to do all types of cooking described above.

2.2.2 HEAT-TRANSFER TYPE OF COOKERS:

One of the drawbacks of the conventional type of solar cooker is that it cannot cook food all the time such as in the evening , in the cloudy weather, inside a house, etc. These drawbacks led to development heat transfer type of cookers.

In these systems the solar energy is stored in a separate 'system' and then it is used at some other place and time for cooking etc. Chemicals such as calcium chloride, magnesium chloride, ammonia etc are used for this purpose. A little research has been done on this type of solar cooking because of cost and limited cooking that can be performed with these.

Already a solar cooker has been developed where the

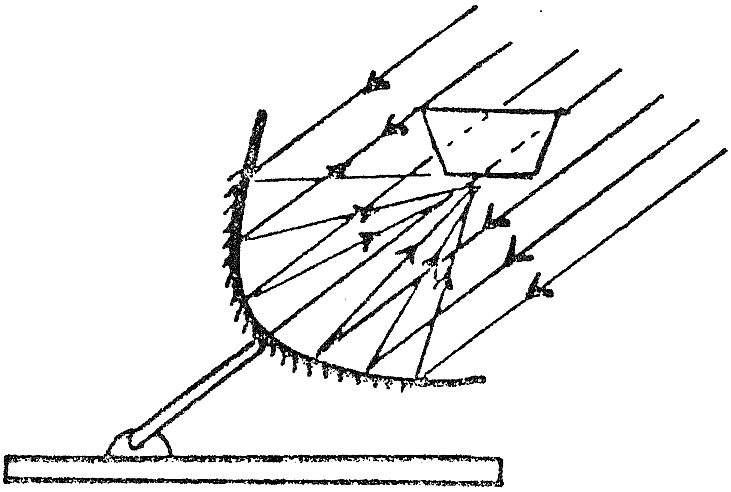


fig. 2.1 Concentrating type of solar cooker

working medium as liquid oil was heated upto 250 °C in the solar collector and pumped inside the house for cooking.

2.2.3 HOT-BOX SOLAR COOKERS:

These are most prominent from the practical point of view. Most of the cookers present in the market fall underr this category.They are popular due to

(a) comparatively low cost,

(b) ease of handling and

(c) reasonable performance.

Hot-Box cookers (fig. 2.2) essentially consists of a insulated, blackened rectangular chamber. The top side of the chamber is made of double glass cover and other sides are heavily insulated serving as door. Solar energy is collected through this cover.Vessels containing food are put inside the chamber through this door. Vessels and the inside surface of the cooker are blackened. When the cooker is exposed to the sun, the solar energy transmits through the glass inside the cooker, heats up the absorber plate and the vessels which, in turn, heats the food content. Some degree of concentration of the solar radiation is also obtained by fixing a mirror reflector on one side of the box.

The insulated chamber acts just like a miniature greenhouse. Solar radiation (fig. 2.3) of the wavelength of the order of 0.4 to 2.5 micrometer can pass through the glass but the thermal radiation emitted by the pots and the absorber plates, of the wavelength greater than 2.5 micro meter, cannot pass through it. Hence the glass and the absorber assembly traps the solar radiation inside the chamber.

Temperature ranging from 75 ^{0}C to 125 ^{0}C are generally

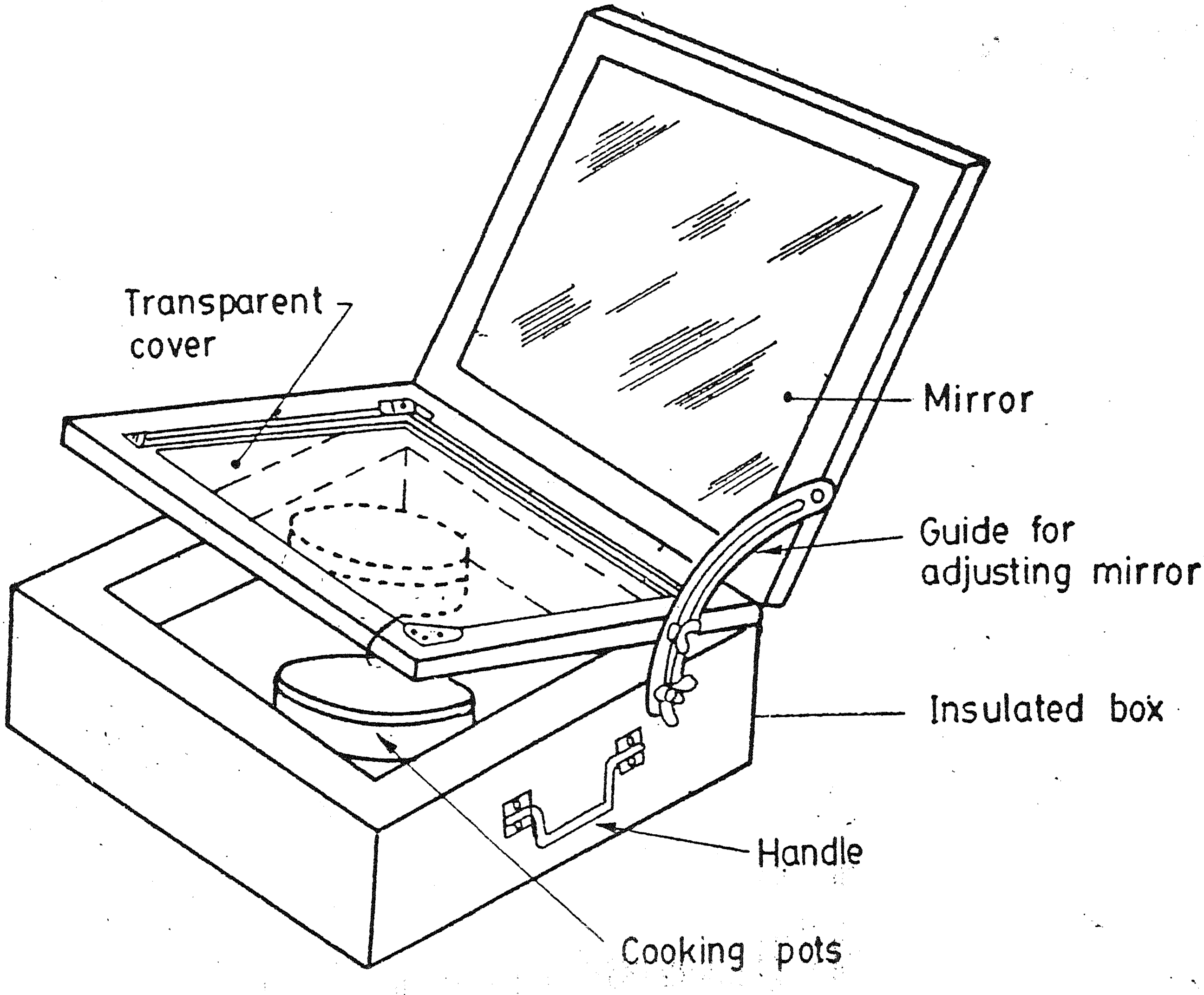


fig. 2.2 Hot-box type solar cooker

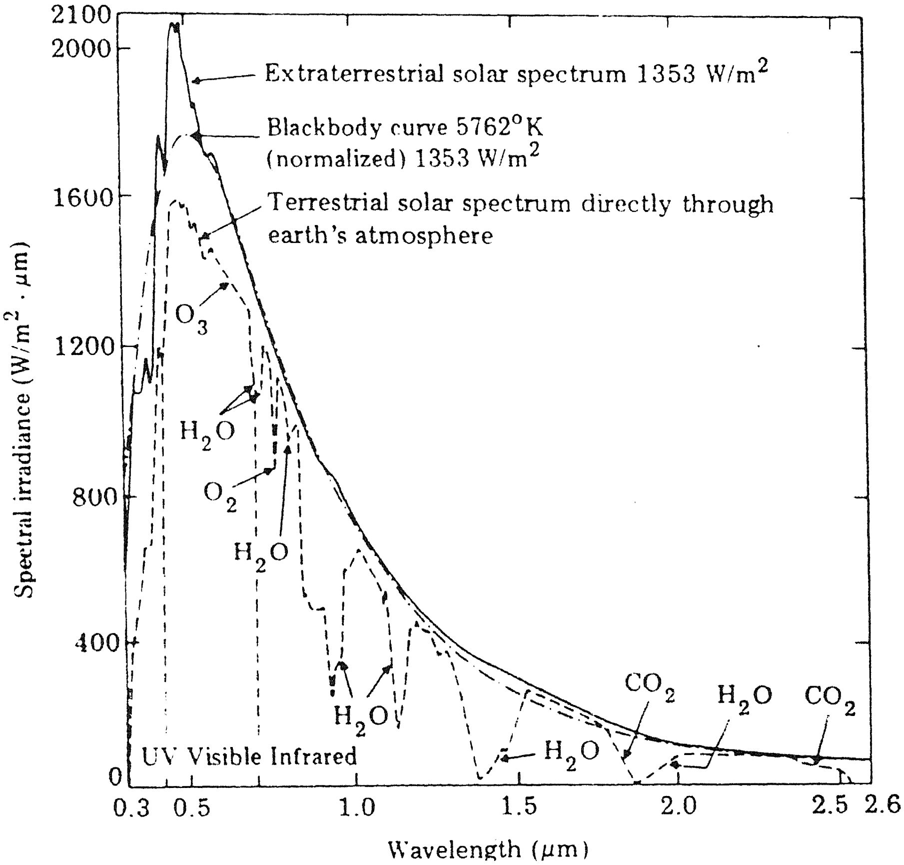


Fig. 2.3 Spectral distribution of extraterrestrial and terrestrial solar energy

attained. Hence only boiling and baking type of cooking can be performed. These are very simple to use. Only the item to be cooked is to be placed inside the cooker and then very little attention is required. It has to be aligned towards the sun only two to three times while cooking.

2.2.4 HYBRID SOLAR COOKER:

As the hot-box solar cooker cannot cook food all the time and moreover many time it so happens that the food remains uncooked due to less solar radiation. So for making it usable all the time, a supplementary source of energy is provided. The concept of the hybrid solar cooker culminated from the need of continuing cooking even during the interruption of the sun by clouds, dust etc. The first successful hybrid solar cooker with electricity backup was developed in 1986 for urban areas as a B. Tech. project. The same was repeated using biogas back up in 1987 for rural areas.One more cooker was design and tested in 1990 [48] in which reflector was dispensed with for rural areas. Realising its versatility, the system got commercialized. It is available in market in abundance. The sales rate is quite high.

At present few models of this type of solar cookers are present in the market. In these models electric heaters are attached to the bottom of the absorber plate. They consume very little amount of electric energy. There is no reference available in the literature about these types of cookers.

CHAPTER 3

LITERATURE SURVEY AND THE PRESENT WORK

Although the concept of solar cooking is known for more than 100 years, they have not found the general acceptance yet. The lack of acceptance is not simply a matter of economics, technology or social/cultural problems but rather a complex mix of all. There is also problem of inadequate programmes of instruction, interaction and follow-up between the sociologist/technologists and the users themselves. Literature survey was done to find out the reasons for this, as well as to know the present state of the technology and to compile the information available on solar cookers at one place.

3.1 LITERATURE SURVEY :

The first oven type solar cooker was introduced by Telkes (1959). Among the various types of solar cookers, the oven type solar cooker is known to be the best in terms of efficiency and economics [1]. Hoda [2] reached a similar conclusion after testing a variety of solar cookers. Ghosh [3] has tested a new type of SUN cooker in which high temperatures were attained. Osman [4] investigated several types of solar cookers and found out that the oven type of solar cookers are most appropriate for rural application in Egypt. Khalifa [5] introduced several novel concepts by developing insulated solar ovens that

contain vapour tight and hence, spill proof pots.

Tiwari and Yadav [6] proposed that door should be at the base of the cooker. This will reduce the heat loss to the ambient whenever the door is opened. Further this will reduce the time for second cooking. Pande and Thanvi [7] designed and developed a new cooker with tilted cover and two reflectors for maximum energy capture in stationary mode. Taha et al. [8] developed a spiral concentrator coupled to an insulated and double-glazed receiver that compared well with the parabolic dish in terms of efficiency. Temperatures as high as 180 °C were attained. Groupp et al. [9] presented a advanced version of the box-type solar cooker with a fixed cooking vessel for better thermal contact. They concluded that it gives enhanced thermal performance.

Khalifa et al. [10] have presented numerical modelling and experimental testing of a solar grill suitable for use in camps. Hall et al. [11] have discussed cooking with stored solar energy. Forber et al. [12] have designed a hydraulic solar powered tracking device.

Buxey [13], Walton et al. [14], Nahar et al. [15], Kammen et al. [16] and Kandpal et al. [17] discussed economics, scope and problems associated with the solar cookers. Malhotra et al. [18] in their technical note have pointed that cooking chamber volume has significant effect on the performance of the cooker. Vishya [19] have tested a hot box solar cooker and concluded that it is not possible to attain 100 °C in the winter. Dang [20] did the analytical study of a solar cooker augmented with a booster mirror using phase change material as storage. Mullick et al. [21] has given thermal test procedure for box-type solar cookers. Yadav

and Tiwari [22] have presented a very simple mathematical model forbox-type cookers. Khalifa et al. [23] have presented computer simulation of a solar pressure cooker. They found that a smaller cooker performs better than a bigger one due to less thermal mass. Channiwala et al. [24] have given a correlation based on the experimental for the determination of top loss coefficient of a box type solar cooker. Das et al. [40] has done extensive work on modelling and simulation of box-type solar cookers. They have concluded that the application of black paint on the vessels is not necessary. But as this conclusion is reached through simulation work it needs to be validated experimentally.

3.2 MERITS OF SOLAR COOKING :

Some of the merits of solar cooking over the conventional means of cooking are listed here :

1. There is no fuel cost due to the use of solar energy.
2. It is completely clean process. There are no by-products of combustion. Hece it does not add to the global warming gases.
3. The localized burning of the food is eliminated.
4. Cooking is done slowly which gives better quality food.
5. There is no fear of burning of food stuff as the temperature inside the cooker does not reach the burning temperature of food stuff.
6. Solar cooking does not require continuous attention on cooking.
7. There is no fear of accidents like bursting of pressure

cooker.

8. As solar energy, an ever green source of energy is used, there is no problem like loss of forestry or fossil fuel.

9. Due to slow cooking process in the solar cooker proteins are not destroyed.

3.3 DEFICIENCIES OF EXISTING DESIGN :

At present only hot-box type solar cooker is being commercially manufactured. Some of the drawbacks of this type of solar cooker are listed here ;

1. Its difficult to cook two meals a day. This problem is more prominent in winter days when solar radiation is very less. Sometimes even one meal is not possible to cook.

2. Cooking time required for solar cooking is higher than that required for conventional means of cooking.

3. In comparison to conventional type of cooking appliances solar cookers are difficult to handle due to following reasons :

    a. Reflector is bulky thus increases the total weight of the solar cooker, causing difficult handling and risk of breaking it while handling.

    b. It is necessary to track the cooker and to adjust the reflector time to time for fast cooking. Thus user is exposed to sun rays

frequently.

c. Access to the cooking vessels is via the glass door which is troublesome. Moreover the glass cover may break due to falling.

4. All types of cooking can not be performed. Frying and roasting which requires temperatures ranging from 125° C to 250 °C are not possible.

5. There are some social taboos and customs which prevent people from accepting solar cooking. It requirescooking to be done in the open which is often socially unacceptable.

6 Economic conditions of a large section of society is not such that they cannot afford the cost of a solar cooker.

3.4 PRESENT WORK :

3.4.1 PURPOSE OF THE PRESENT WORK :

The fossil fuel reserves are depleting fast and the day is not far when we will find ourselves in a situation of energy crunch if alternative and non-conventional resources are not harnessed. As already discussed solar energy is the best alternative. Present work was carried out with the following purposes:

1. to develop a design which can make the handling of solar cooker easy,
2. to analyze scientifically the concept of hybridization of the solar cooker &

3. to find the possibilities of using the new design for the purpose of community cooking.

3.4.2 MODIFICATIONS IN THE PRESENT DESIGN :

To achieve above objectives following modifications are made in the present design :

(1.) TILTED GLASS COVER :

The glass cover of the cooker is made tilted to the horizontal. This has following effects:

i. Solar radiation intercepted by the glass cover is increased by 50 % to 60 % (fig. 3.1). This is specially advantageous in the winter days when solar radiation intensity is less.

ii. Inside volume of the cooker is increased. More food can be cooked in one loading.

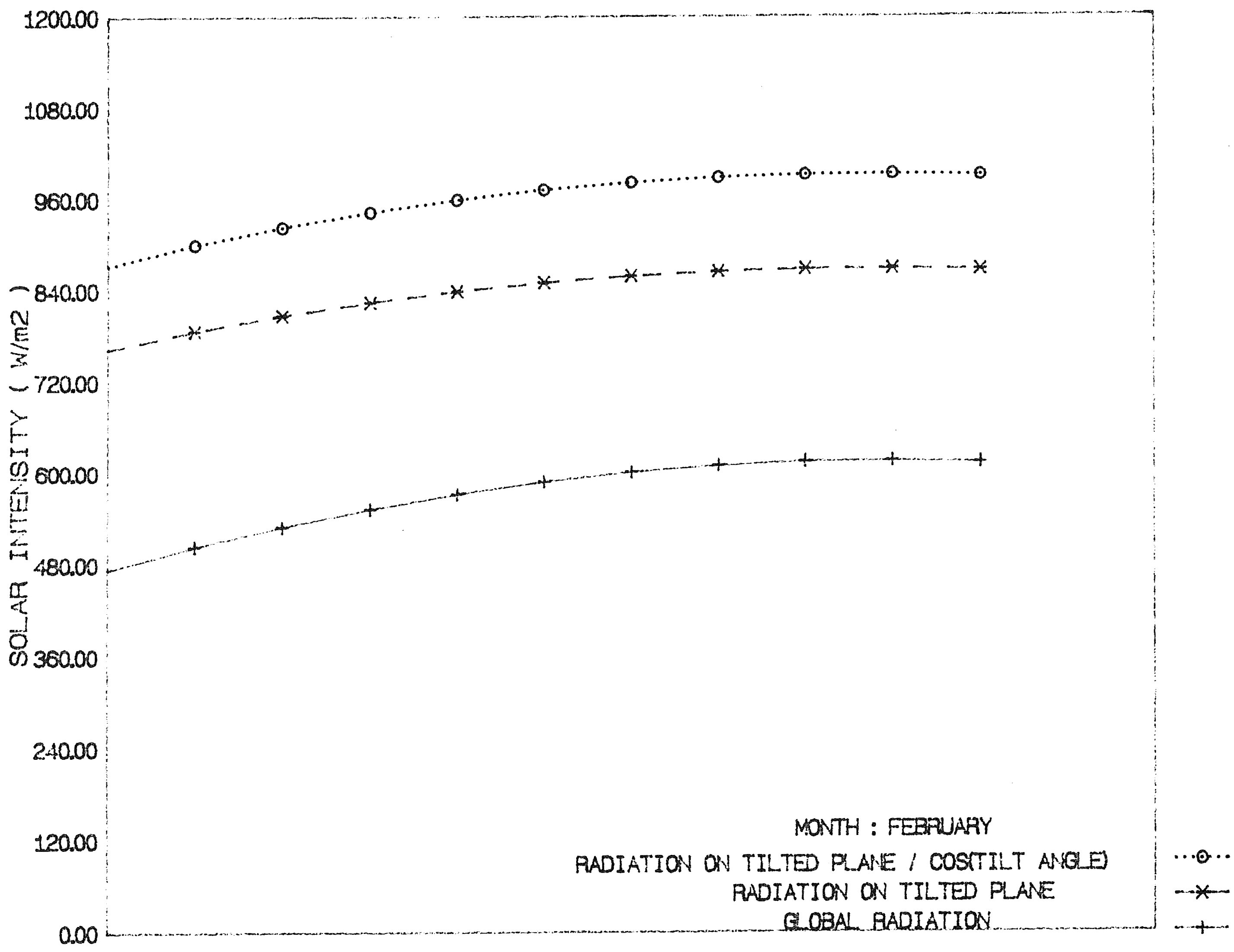
iii. Total thermal mass of the unloaded cooker is increased. This will increase the amount of energy stored by body of the cooker.

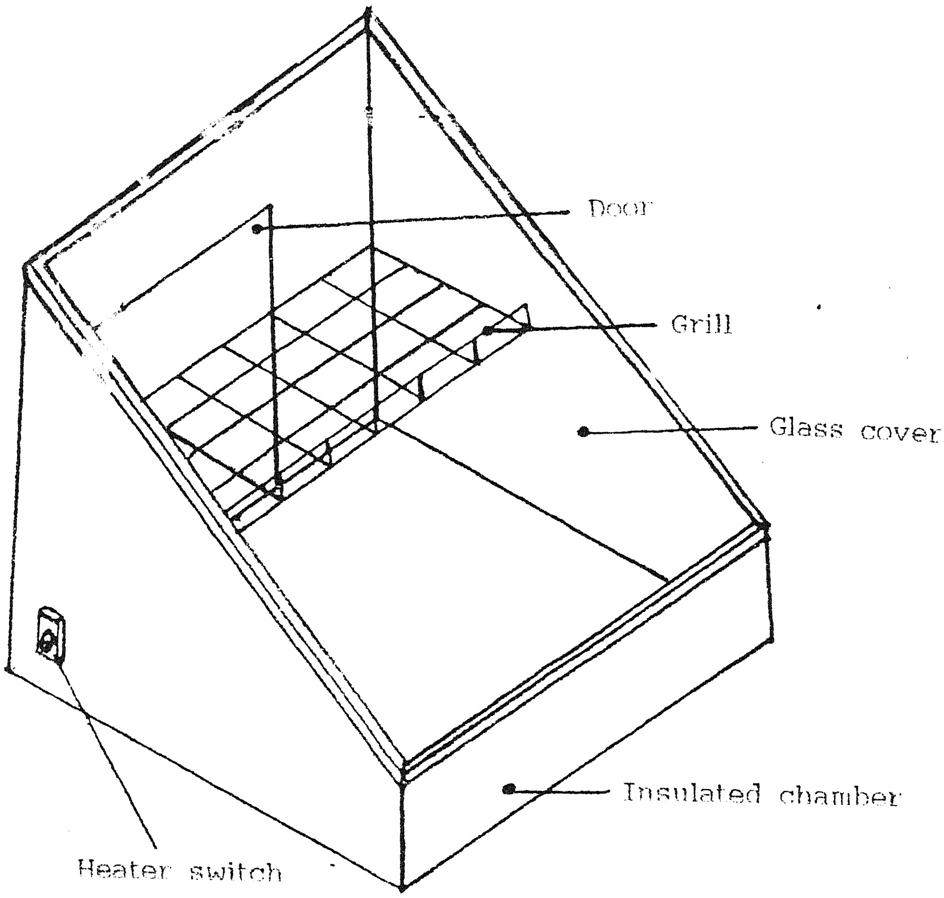
iv. Heat loss area is increased.

(2) REFLECTOR :

Two cases are considered :

1. In first one, cooker without a reflector is considered (fig. 3.1). This has made the handling of the cooker very easy as the bulky reflector is removed. There is no need


SOLAR INTENSITY (W/m2)
1200.00
1080.00
960.00
840.00
720.00
600.00
480.00
360.00
240.00
120.00
0.00
MONTH : FEBRUARY
RADIATION ON TILTED PLANE / COS(TILT ANGLE)
RADIATION ON TILTED PLANE
GLOBAL RADIATION



'ig. 3.2 New type of hybrid type solar cooker (without reflector)

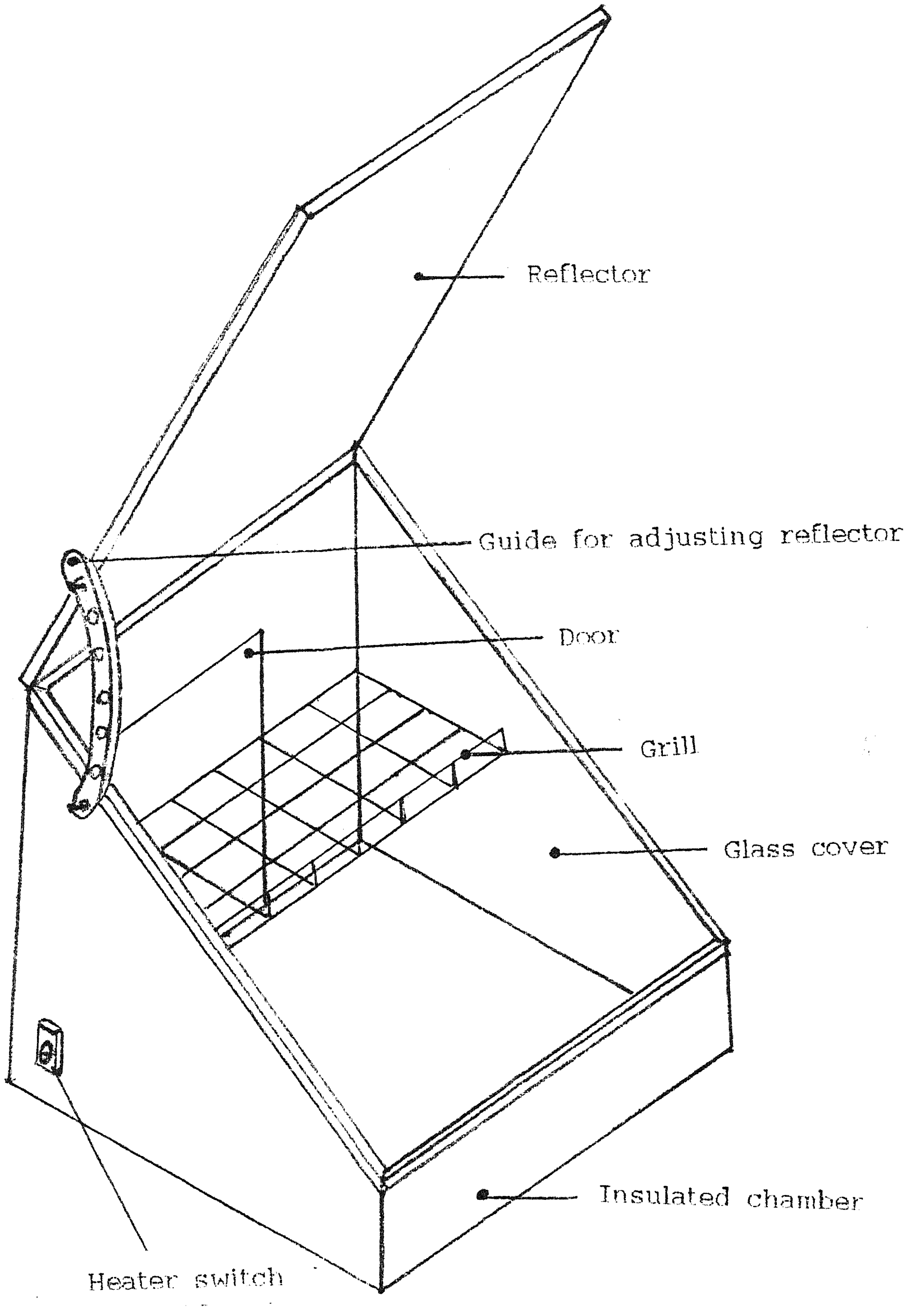


Fig. 3.3 New type of hybrid type solar cooker (with reflector)

of tracking.

2. In the second case, cooker with a simple aluminum reflector is considered (fig. 3.3). As for the protection of the outer glass cover a metal cover is necessary, a light weight aluminum reflector is used in the second design. Still the handling of reflector is easier than the conventional type glass reflector.

This ease of handling is obtained at the cost of reduced solar radiation collection.

(3) DOOR :

The door is transferred to the back side of the cooker. This has made the handling of the vessels very easy. Further whenever the door is opened, heat loss to the ambient is reduced.

(4) SECOND TIER :

The cooker is made two tier. A grill is provided above the lower vessels. Maximum two vessels can be put on this grill. Energy to the pots is transferred by hot air rising from the lower vessels and absorber plate, by radiative heat exchange from all the heated surfaces and by conduction from the grill. The presence of the upper vessels reduces the solar radiation incident on the two lower vessels.

(5) SUPPLEMENTARY ENERGY SOURCE :

An supplementary energy source is provided to heat the bottom plate. This can be a electric heater or a biogas burner.

Complete design description of the cooker is given in

the chapter 5.

3.4.3 PROCEDURE :

To gain complete insight of the performance of the new design, both theoretical and experimental work is done. A mathematical model is proposed for the new design. Computer simulation is carried out to evaluate the performance of the new cooker and to see the effect of different system parameters on its performance. A cooker of new design was fabricated and tested to check the computational results as well as to study its working under different conditions.

CHAPTER 4

ANALYSIS AND MATHEMATICAL MODELLING

Computer simulation is the mathematical representation of the physical and thermal behaviour of a system and simulating it by solving the mathematical equations therein subjected to certain constraints and conditions.

4.1 OBJECTIVES OF THE THEORITICAL ANALYSIS :

The present simulation work is carried out with the following objectives :

i. To evolve the perfomance of the new solar cooker under differnt ambient conditions year round.

ii. To study the effects of different parameters like size of the glasses in the cover, material and size of the vessels and absorber plate, emmisivity of the absorber plate etc.

iii. To estimate the most economical rate of supplementry energy supply.

iv. To study the effect of size of the cooker on its perfomance.

v. To check the theoritical results with the experimental results.

4.2 DESCRIPTION OF THE COOKER :

Fig. (4.1) shows the sketch of the cooker which was used for simulation purpose. The solar cooker is a doubled wall box made out of metal sheet. The space between the outer and inner casing is filled with a proper insulating material. The size of

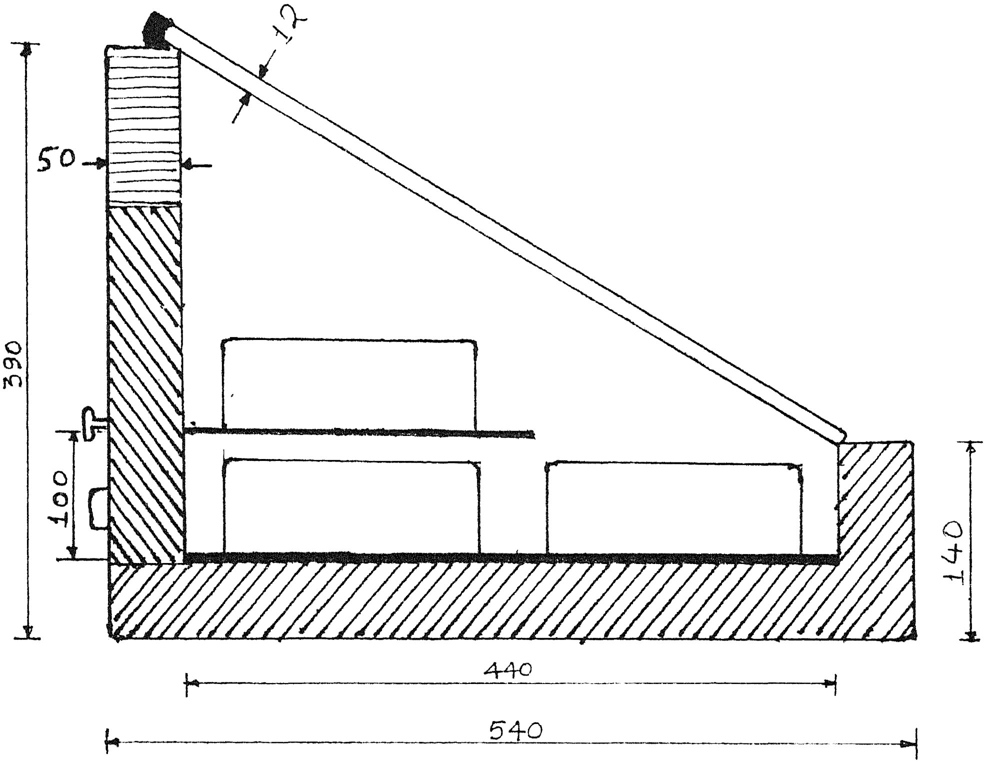


Fig. 4.1 Schematic diagram of the cooker.

the cover plate is close to the projected area of the box type conventional solar cooker having reflecting mirror. Due to this concept the height of the cooker on the backside becomes too much. Hence, provisions have been made to keep more pots. Glass cover system contain two glasses. There is no reflector. There are four vessels on the bottom plate and two pots on the grill. Grill height is equal to the height of the front side of the inner casing plus some clearance. A homogenous fluid is present in all the vessels. There is a gap of one cm between the vessel cover and the top of the fluid surface.

4.3 THERMAL ANALYSIS :

Solar radiation reaching the inclined glass cover has three components- direct beam radition, diffuse radiation and reflected radiation from the ground. A part of this radiation is reflected and absorbed by the glass cover and the rest transmitted part of the energy is absorbed by the absorber plates and the vessels. The absorber plate transfers heat to the vessel by conduction, convection and radition. Vessel in turn transfers heat to its contents. A part of the transmitted energy is lost to the surroundings through glass cover and the back of the absorber plates and a part is stored in the different parts of cooker body.

The temperature of a component of the cooker at any time can be calculated by solving the following energy balance equation

ENERGY IN -- ENERGY OUT = HEAT CAPACITY X TEMPERATURE RISE

In mathematical terms,

$$Ein - Eout = Mcp \times DT \tag{4.1}$$

or

$$Q_{in} - Q_{out} = Mcp \times \frac{dT}{dt} \tag{4.2}$$

4.4 PAST WORK ON THE MATHEMATICAL MODELING OF SOLAR COOKERS :

Many investigators have proposed different mathematical models for the transient analysis of the solar cookers. But no model presented so far is adequate to predict satisfactory results. Some of the inadequacies of these models are pointed here,

i. In most of the models the radiative heat exchange inside the cooker is neglected inspite of the fact that radiative heat transfer is quite significant among the different surfaces of the cooker. The obvious reason for this assumption is the complexity of the calculation of radiative heat transfer.

ii. Temperature of the whole vessel body is assumed uniform. Different surfaces of the vessel are exposed to different conditions. Vessel cover and front side of the vessel receives direct solar radiation. Vessel back is in contact with the absorber plate. Vessel cover is exchanging heat with the contents by radition and convection through air while vessel back and a part of vessel side are in direct contact with the contents. Due to these differences certainly the temperature and the heat transfer rate from the different surfaces of the vessel will be differnt.

iii. The models in which the vessel cover and the rest of the vessel are analysed separately, no conducdtive heat transfer is considered between them. Due to high conductivity of the vessel material there may be

significant heat transfer by conduction.

iv. All side plates are assumed to be at the same temperature. In the actual case as the back of the side plate is always receiving direct solar radiation while the front of the side plate is never receiving direct solar radiation. Hence they cannot be ideally at the same temperature.

v. In some models the vessel contents are assumes to be in contact with the vessel cover which is again not a practical situation. There is always some gap. Hence contact resistance has to be considered.

vi. In some models the heat capacity of the glass, absorber plate, vessels are neglected. Significant amount of input energy is absorbed by these components.

Keeping in view all these inadequacies of the present models, an extensive model is proposed here for the new solar cooker design. This model can also be extended for the conventional cooker design.

4.5 DIVISION OF THE COOKER :

For considering the energy balance of the cooker it is divided into several parts with the components exposed to same conditions are considered to be at uniform temperature at any particular time. Itis divided into following parts (fig.4.2) :

1. VESSELS : All the vessels are treated as separate units. Looking from above the upper vessels are designated as u1 and u2 while lower vessels are designated as d1, d2, d3 and d4 clockwise

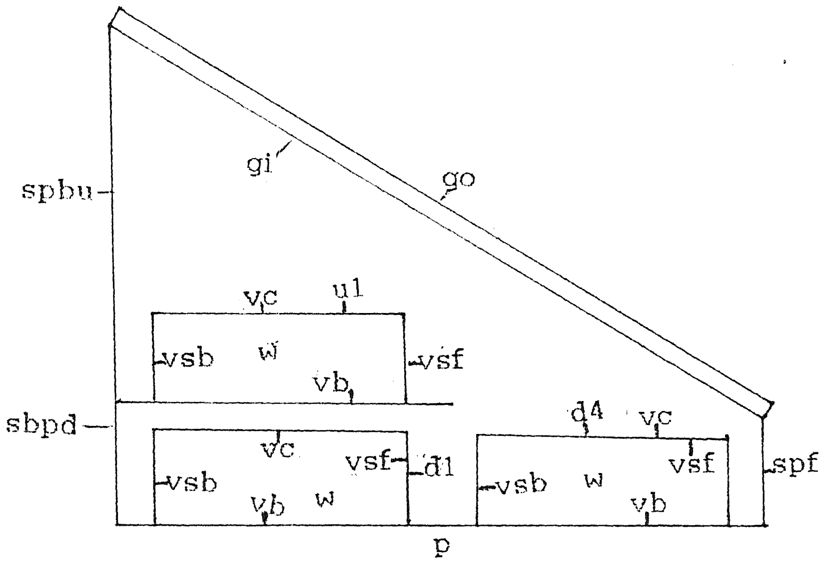


Fig. 4.2 Computational domain

starting from left back corner (fig. 4.3). Each vessel is divided in four parts :

a. vessel cover

b. vessel bottom

c. vessel side- front

d. vessel side-back

2. PLATE : The bottom portion of the absorber plate is referred as plate.

3. SIDE PLATE : The side portion of the absorber plate is divided in five parts :

a. side plate-back :It is further divided into two parts:

a.1. side plate-back-up.

a.2. side plate-back-down

b. side plate-side :

b.1. side plate-side-left

b.2. side plate-side-right

c. side plate-front.

4. GLASS COVER SYSTEM :

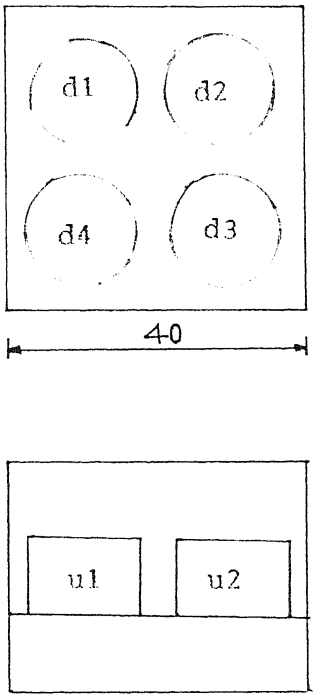
It contains two glasses. Each glass is considered separately.

5. VESSEL CONTENTS.

6. AIR INSIDE THE COOKER :

For a cooker loaded with six pots and with double glazing there are 40 components and hence 40 temperature zones inside the cooker.

4. ASSUMPTIONS :



ALL DIMENSIONS ARE [illegible]

Fig. 4.3 Arrangement of the vessels

While writing the energy balance equations, the following assumptions are made :

1. The whole body of any component is assumed to be at uniform temperature at any instant.
2. Solar radition is uniformly distributed on the glass cover.
3. There is no radiative heat transfer among the vessels on the bottom plate and between the vessels on the grill. But radiative heat transfer among the upper vessels and lowere vessels is considered.
4. Cooker is perfectly sealed to the ambient.
5. When heater is being used its energy input is uniformly distributed over the bottom plate.

4.7 ENERGY BALANCE EQUATIONS :

Energy balance equations for the different components are given below (see the nomenclature for the definitions of the symbols) :

4.7.1 VESSELS :

4.7.1.a Upper Vessels : Energy baslance equation for the upper vessel (u1) is given here. The energy balance equation for the other upper vessel (u2)is same.

4.7.1.a1 Vessel Cover (up1) :

$$(M\ cp)_{vcu1} \frac{dT_{vcu1}}{dt} = Q_{c,vcu1-a} + Q_{cr,vcu1-wu1}$$
$$+ Q_{cd,vcu1-(vsfu1,vsbu1)}$$
$$+ Q_{r,vcu1-(gi,spbu,spbd,spsl,spsr)}$$

$$+ \text{isvcu1} \qquad (4.3)$$

4.7.1.a2 Vessel bottom (up 1) :

$$(M\ Cp)_{vbu1} \frac{dT_{vbu1}}{dt} = Q_{c,vbu1-a} + Q_{c,vbu1-wu1}$$
$$+ Q_{cd,vbu1-(vsfu1,vsbu1)}$$
$$+ Q_{r,vbu1-(spbd,spsl,spsr,spf,p,vcd1,vcd2)}$$
$$+ Q_{r,vbu1-(vcd3,vcd4,vsbd3,vsbd4)} \qquad (4.4)$$

4.7.1.a3 Vessel-Side-front (up 1) :

$$(M\ Cp)_{vsfu1} \frac{dT_{vsfu1}}{dt} = Q_{c,vsfu1-a} + Q_{c,vsfu1-wu1}$$
$$+ Q_{cd,vsfu1-(vcu1,vbu1,vsbu1)}$$
$$+ Q_{r,vsfu1-(gi,spsl,spsr,spf,p)}$$
$$+ Q_{r,vbu1-(vcd3,vcd4,vsbd3,vsbd4)}$$
$$+ \text{isvsfu1} \qquad (4.5)$$

4.7.1.a4 Vessel-Side-back (up 1) :

$$(M\ Cp)_{vsbu1} \frac{dT_{vsbu1}}{dt} = Q_{c,vsbu1-a} + Q_{c,vsbu1-wu1}$$
$$+ Q_{cd,vsbu1-(vsfu1,vsbu1)}$$
$$+ Q_{r,vsbu1-(gi,spbu,spbd,spsl,spsr)} \qquad (4.6)$$

4.7.1.b Lower Vessels (1 & 2): Energy baslance equation for the lower vessel (d1) is given here. The energy balance equation for the one other lower vessel (d2)is same.

4.7.1.b1 Vessel Cover (down 1) :

$$(M\ Cp)_{vcd1} \frac{dT_{vcd1}}{dt} = Q_{c,vcd1-a} + Q_{cr,vcd1-wd1}$$
$$+ Q_{cd,vcd1-(vsfd1,vsbd1)}$$
$$+ Q_{r,vcd1-(gi,spbu,spbd,spsl,spsr,spf)}$$
$$+ Q_{r,vcd1-(vbu1,vbu2)}$$
$$+ \text{isvcd1} \qquad (4.7)$$

4.7.1.b2 Vessel bottom (down 1) :

$$(M\ Cp)_{vbd1} \frac{dT_{vbd1}}{dt} = Q_{c,vbu1-wu1} + Q_{ct,vbd1-p}$$

$$+ Q_{cd,vbd1-(vsfd1,vsbd1)} \tag{4.8}$$

4.7.1.b3 Vessel-Side-front (down 1) :

$$(M\ cp)_{vsfd1}\frac{dT_{vsfd1}}{dt} = Q_{c,vsfd1-a} + Q_{c,vsfd1-wd1} + Q_{cd,vsdu1-(vcd1,vbd1,vsbd1)} + Q_{r,vsfd1-(gi,spsl,spsr,spf,p)} + \bar{I}svsfd1 \tag{4.9}$$

4.7.1.b4 Vessel-Side-back (down 1) :

$$(M\ cp)_{vsbd1}\frac{dT_{vsbu1}}{dt} = Q_{c,vsbd1-a} + Q_{c,vsdu1-wd1} + Q_{cd,vsbd1-(vsfd1,vsbd1)} + Q_{r,vsbd1-(spbu,spbd,spsl,spsr)} \tag{4.10}$$

4.7.1.c Lower Vessels (3 & 4): Energy baslance equation for the lower vessel (d3) is given here. The energy balance equation for the one other lower vessel (d4)is same.

4.7.1.c1 Vessel Cover (down 3) :

$$(M\ cp)_{vcd3}\frac{dT_{vcd3}}{dt} = Q_{c,vcd3-a} + Q_{cr,vcd3-wd3} + Q_{cd,vcd3-(vsfd3,vsbd3)} + Q_{r,vcd3-(gi,spbu,spbd,spsl,spsr,spf)} + Q_{r,vcd3-(vbu1,vbu2,vsfu1,vsfu2)} + \bar{I}svcd3 \tag{4.11}$$

4.7.1.c2 Vessel bottom (down 3) :

$$(M\ cp)_{vbd3}\frac{dT_{vbd3}}{dt} = Q_{c,vbu3-wu3} + Q_{ct,vbd3-p} + Q_{cd,vbd3-(vsfd3,vsbd3)} \tag{4.12}$$

4.7.1.c3 Vessel-Side-front (down 3) :

$$(M\ cp)_{vsfd3}\frac{dT_{vsfd3}}{dt} = Q_{c,vsfd3-a} + Q_{c,vsfd3-wd3} + Q_{cd,vsdu3-(vcd3,vbd3,vsbd3)} + Q_{r,vsfd3-(gi,spsl,spsr,spf,p)} + \bar{I}svsfd3 \tag{4.13}$$

4.7.1.c4 Vessel-Side-back (down 3) :

$$(M\ Cp)_{vsbd3} \frac{dT_{vsbu3}}{dt} = Q_{c,vsbd3-a} + Q_{c,vsd3-wd3} + Q_{cd,vsbd3-(vsfd3,vsbd3)} + Q_{r,vsbd3-(spbu,spbd,spsl,spsr)} \quad (4.14)$$

4.7.2 PLATE :

$$(Mcp)_p \frac{dT_p}{dt} = Q_{c,p-q} + Q_{ct,p-(vdb1,vdb2,vdb3,vdb4)} + Q_{cd,p-(spsl,spsr,spbd,spt)} + Q_{cdc,p-i} + Q_{r,p-(vsfd1,vsfd2,vsfd3.vsfd4)} + Q_{r,p-(vsbd1,vsbd2,vsbd3,vsbd4)} + Q_{r,p-(spsl,spsr,spf,spbd,spbu,gi)} + Q_{r,p-(vsfu1,vsfu2,vbu1,vbu2)} + Isp \quad (4.14)$$

4.7.2 Side plate

4.7.2.a Side Plate - back

4.7.2.a1 Side plate - back-up

$$(Mcp)_{spbu} \frac{dT_{spbu}}{dt} = Q_{c,spbu-a} + Q_{cd,spbu-(spbd,spsl,spsr)} + Q_{cdc,spbu-i} + Q_{r,spbu-(gi,spsl,spsr,spf,p)} + Q_{r,spbu-(vcu1,vcu2,vsbu1,vsbu2)} + Q_{r,spbu-(vcd1,vcd2,vcd3,vcd4)} + Q_{r,spbu-(vsbd1,vsbd2,vsbd3,vsbd4)} + Isspbu \quad (4.15)$$

4.7.2.a2 Side plate - back - down

$$(Mcp)_{spbd} \frac{dT_{spbd}}{dt} = Q_{c,spd-u} + Q_{cd,spbd-(spbu,spsl,spsr,p)} + Q_{cdc,spbd-i} + Q_{r,spbd-(gi,spsl,spsr,spt,p)} + Q_{r,spbd-(vbu1,vbu2,vsbu1,vsbu2)} + Q_{r,spbd-(vcd1,vcd2,vcd3,vcd4)} + Q_{r,spbd-(vsbd1,vsbd2,vsbd3,vsbd4)} + Ispbd \quad (4.16)$$

4.7.2.b Side plate - side : Energy equation for the side plate -

side - left is given here. The energy balance equation for the side plate - side - right is same.

$$(Mcp)_{spsl}\frac{dT_{spsl}}{dt} = Q_{c,spsl-a} + Q_{cd,spsl-(spbu,spbd,spf,p)} + Q_{cdc,spsl-i} + Q_{r,spsl-(gi,spsr,spbu,spbd,spt,p)} + Q_{r,spsl-(vbu1,vbu2,vsfu1,vsfu2,vsbu1,vsbu2)} + Q_{r,spsl-(vcd1,vcd2,vcd3,vcd4)} + Q_{r,spsl-(vsfd3,vsfd2,vsfd3,vsfd4)} + Q_{r,spsl-(vsbd1,vsbd2,vsbd3,vsbd4)} + \bar{I}sspsl \qquad (4.17)$$

4.7.2.c Side plate - front

$$(Mcp)_{spf}\frac{dT_{spf}}{dt} = Q_{c,spf-a} + Q_{cd,spf-(spsl,spsr,p)} + Q_{cdc,spf-i} + Q_{r,spf-(spsr,spsl,spbu,spbd,p,gi)} + Q_{r,spf-(vsfu1,vsfu2)} + Q_{r,spf-(vcd1,vcd2,vcd3,vcd4)} + Q_{r,spf-(vstd1,vstd2,vstd3,vstd4)} \qquad (4.18)$$

4.7.3 Glass cover system

4.7.3.a Inner glass

$$(Mcp)_{gi}\frac{dT_{gi}}{dt} = Q_{c.gi-go} + Q_{r,gi-go} + Q_{r,gi-(vcu1,vcu2,vsfu1,vsfu2,vsbu1,vsbu2)} + Q_{r,gi-(spsl,spsr,spbu,spsd,spbd,spf,p)} + Q_{r,gi-(vcd1,vcd2,vcd3,vcd4)} + Q_{r,gi-(vsfd1,vsfd2,vsfd3,vsfd4)} + Q_{r,gi-(vsbd1,vsbd2,vsbd3,vsbd4)} + \bar{I}sagi \qquad (4.19)$$

4.7.3.b Outer glass :

$$(Mcp)_{g0}\frac{dT_{go}}{dt} = Q_{c,go-i} + Q_{r,go-gi} + Q_{c,go-gi} + Q_{c,go-gi} + \bar{I}sago \qquad (4.20)$$

4.7.4 Vessel contents :

Energy balance equation for contents of upper vessel (1) is given here. The energy balance equation for the contents of all other vessel is same.

$$(Mcp)_{wu1} \frac{dT_{wu1}}{dt} = Q_{c,wu1-(vbu1,vsfu1,vsbu1,vcu1)} + Q_{r,wu1-vcu1} \qquad (4.21)$$

4.7.5 Air inside the cooler :

$$(Mcp)_a \frac{dT_a}{dt} = Q_{c,a-(gi,spbu,spbd,spsl,spsr,spf,p)} + Q_{c,a-(vcu1,vcu2,vcd1,vcd2,vcd3,vcd4)} + Q_{c,a-(vsfu1,vsfu2,vsfd1,vsfd2,vsfd3,vsfd4)} + Q_{c,a-(vsbu1,vsbu2,vsbd1,vsbd2,vsbd3,vsbd4)} + Q_{c,a-(vbu1,vbu2)} \qquad (4.22)$$

4.8 SOLAR RADIATION CALCULATION :

Solar radiation is calculated by the method given in the ASHRAE hanbook [42,45].The method is based on an exponentialdecay model in which the beam radiation decreases with increase in the distance traversed through the atmosphere. The global radiation reaching the earth is given by (fig. 4.4 and 4.5),

$$I_g = I_b + I_d \qquad (4.23)$$

$$I_b = I_{bn} \cos \theta_z \qquad (4.24)$$

$$I_{bn} = A \exp(-B / \cos \theta_z) \qquad (4.25)$$

$$I_d = C\ I_{bn} \qquad (4.26)$$

$$\cos \theta_z = \sin L \ \sin \delta + \cos \delta \ \cos W \ \cos L \qquad (4.27)$$

where I_g, I_b , I_d and I_{bn} are global, beam, diffuse and direct radiation intensities respectively. θ_z is the angle of incidence of solar radiation on a horizontal plane., A,B and C

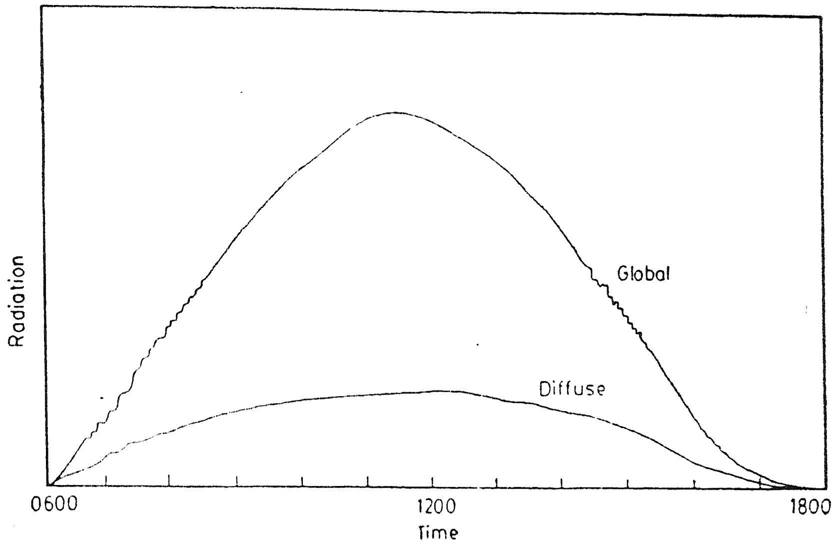


Fig. 4.4 Record of global and diffuse radiation measured on a clear day.

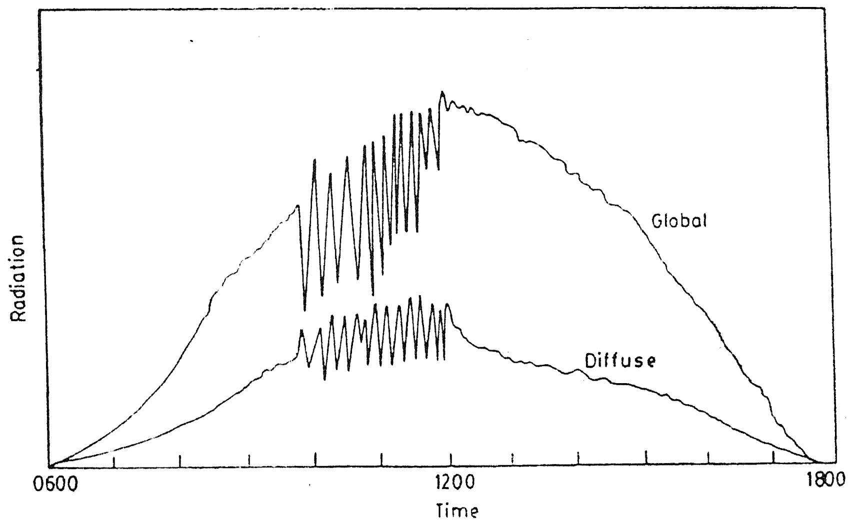


Fig. 4.5 Record of global and diffuse radiation measured on a partly cloudy day

are constants whose values have been determined from the analysis of data for U.S.A (appendix C). The values have been determined for each month since they change during the year because of seasonal changes in the dust and water vapour content of the atmosphere and also because of the changing earth and sun distance (appendix A).

It has been found [42] that predicting radiation in Indian conditions using these values results in high values of the beam radiation and very low values of the diffuse radiation. For the present work, the solar radiation predicted by this methodfor the months of December and February was compared with the measured value. Theoretical values are found to be about 12 % higher than the measured ones. Hence the appropriate factors are multiplied to the theoretical results for the simulation purpose.

Solar radiation on a tilted plane is given by

$$I_t = I_b R_b + I_d R_d + (I_b + I_d) R_r \tag{4.28}$$

$$R_b = \frac{\cos \theta}{\cos \theta z} \tag{4.29}$$

$$R_d = \frac{1 + \cos \beta}{2} \tag{4.30}$$

$$R_r = \rho \left[\frac{1 - \cos \beta}{2} \right] \tag{4.31}$$

$$\cos \theta = \sin \delta \; \sin (\phi - \beta) + \cos \delta \; \cos W \; \cos (\phi - \beta) \tag{4.32}$$

$$\delta = 23.45 \left[\sin \frac{360}{365} (284 + n) \right] \tag{4.33}$$

LAT = standard time $\pm$ 4 (standard longitude - longitude of location) + (equation of time correction)

where R_b, R_d and R_r are the tilt factors for beam, diffuse and reflected radiation, respectively, β is the tilt of the plane. L is the latitude of the place, δ is the declination of the sun, n is the number of day in the year. W is the hour angle (negative in forenoon and positive in the afternoon). It is based on local apparent time i.e. the solar time. ρ is the reflectivity of the ground. Its value is taken equal to 0.2 for the grass and concrete.

The radiation transmitted inside the cooker is given by

$$ris = I_t(1- \tau g- \rho g)\ Ag \tag{4.34}$$

The fraction of the transmitted energy reasching a component is given by

$$ris_{comp} = ris\ \frac{A_{comp}}{Ag}\ \frac{\cos(\theta_{comp})}{\cos(\theta_z)} \tag{4.35}$$

where A_{comp} is the area of the component of the cooker, θ_{comp} is the angle of incidence of the direct solar radiation on the cooker component.

4.9 CONVECTIVE HEAT TRANSFER COEFFICIENTS :

Only natural convection is present inside the cooker. Forced convection due to wind is present at the outer surface of the cooker. It is assumed that the presence of the grill and vessels is not affecting the flow patterns inside the cooker. Further it is assumed that there is no obstruction within the

thermal boundary layer of any suface.

a. Outer surface : Following correlation for the heat transfer coefficient for forced convection over smooth surface is used

$$h_{c,wind} = 8.55 + 2.56\, V_a \qquad (4.36)$$

b. Space between the two glass surfaces : It is treated as a rectangular enclosing and Holland correlation has been used,

$$Nu = 1 + 1.44 \left[1 + \frac{1708}{Gr\ pr\ Cos\beta} \right]^{(+)} \left[1 - \frac{(Sin\ 1.8\ \beta)^{1.6}\ .1708}{Gr\ pr\ Cos\beta} \right] + \left[\left(\frac{Gr\ pr\ Cos\beta}{5830} \right)^{1/3} -1 \right]^{(+)} \qquad (4.37)$$

where Nu is the Nusselt number, Gr is the Grashoff's number and Pr is the Prandtl number. This correlation with the modification for temperature, is used for the calculation of heat transfer coefficient.

c. Correlations for all other convective heat transfer coefficients for heat transfer from heated horizontal and vertical, rectangular and circular, plates and cylinders are taken from different research works (appendix B) [31, 48, 51].

4.10 RADIATIVE HEAT TRANSFER COEFFICIENT :

Radiative heat transfer coefficient is defined as

$$h_{r,i-j} = \frac{\sigma\ (\ T_i + T_j\ )\ (\ T_i^2 + T_j^2\ )}{\frac{1-\varepsilon_j}{\varepsilon_i} + \frac{1}{F_{ij}} + \frac{1-\varepsilon_i}{\varepsilon_j}\ \frac{A_i}{A_j}} \qquad (4.38)$$

where σ is the Stefan-Boltzmann constant, ε is the emmissivity of the surface, F is the view factor between thetwo

surfaces, A is the surface area of the surface, i and j denotes the two surfaces between which raditive heat transfer is taking place.

The view factors are calculated using the formulas given in the references [44,45,46,49,50]. For the calculation of view factor from the circular vessel cover to any other surface, equivalent squares, having same area, were used for the simplification of the problem. Due to the presence of the vessels view of some of the surfaces is obstructed. There is no simple method to calculate the exact view factors for these surfaces. But these can be calculated approximately by first calculating the view factor between the two surfaces without any obstruction. Then this factor can be modified for the obstruction. For the purpose of modification, we need the view factor between the first surface and the obstruction. But as it is not known that how much percentage area of vessel is obstructing the view of any other surface, it is to be assumed judicially by simple observation. Fortunately in the case of solar cooker this can be done easily as only symmetrical surfaces are present.

4.11 CONDUCTION COEFFICIENTS :

Conductive heat transfer is taking place mainly between any two components of absorber plates and vessels and from the adbsorber plate to the outer casing. It is defined as,

$$h_{cd,i-j} = \frac{1}{R_{cd,i-j}} = \frac{K}{\Delta t_{i-j}} = \frac{Q_{cd,i-j}}{A_{i-j}} \qquad (4.39)$$

where $R_{cd,i-j}$ is the equivalent conductive resistance, K

is the conductivity of the material, Δt_{i-j} the distance over which heat conduction is taking place, it is assumed that it is equal to the distance from the centre of one component to the centre of other component, $Q_{cd,i-j}$ is the heat flux due to the conductive heat transfer and A_{i-j} is the cross section area.

4.12 CONTACT RESISTANCE :

Heat transfer from the bottom plate to the vessel back depends upon the contact resistance between the two. Contact resistance is a function of the surface roughness, the material of the two surfaces in contact and the properties of the fluid present between the two surfaces. The value for contact resistance are taken from the experimental investigation carried out by Das et al. [40].

The heat transfer from the vessel cover to the vessel content is by convection and radiation both. Value for this heat transfer coefficient is also taken from the reference [40].

4.13 METHOD OF SIMULATION :

step-wise-steady-state simulation is performed for the mathematical model presented above.

All the energy balance equations can be written in the form

$$\frac{dT_{comp}}{dt} + f2(T_{comp},T_i)\ T_{comp} = f1(T_{comp},T_i) \qquad (4.40)$$

$$\text{where} \quad f1(T_{comp},T_i) = A_{comp} \sum_{i=1}^{i=n} h_{comp-i}\ T_i + C_1 \qquad (4.41)$$

$$f2(T_{comp}, T_i) = A_{comp} \sum_{i=1}^{i=n} h_{comp-i} \; T_i \tag{4.42}$$

T_i is the temperature of other components with which the particular component is exchanging heat energy, C_1 is a constant. Above equation is a non-linear differential equation of first degree and first order. Its analytical solution is not available. If we consider a very small time interval (of the order of 1 second), so that the values of the functions are almost constant over the time interval, then the above equation will reduce to a linear equation for that particular time interval.

$$\frac{dT_{comp}}{dt} + a \, T_{comp} = b \tag{4.43}$$

If T_b and T_e are the temperature of any component at the begining and end of a time step. The solution of the above differential equation is

$$T_e = (b / a) + (T_b - (b / a)) \exp(- a \, dt)) \tag{4.44}$$

where as the first guess the values of a and b are calculated based on the temperatures of the components at one time step back of the present time. Same procedure is repeated till small changes in the values of T_e are obtained. After calculating temperatures of all the components for a particular time step, next time step is considered.

At the beginning of the simulation the temperatures of all the components are set equal to the ambient temperature. Then selecting a small time step all the energy balance equations are solved. Subroutines and functions are added to calculate the instantaneous solar radiation, convective, radiative and conductive heat transfer coefficients and instantaneous properties

of the vessel contents and air.

The computer simulation is done with different system parameters, the details of which are given in the appendix D.

CHAPTER 5

EXPERIMENTAL SET-UP AND TEST PROCEDURE

The experiment analysis includes the design, fabrication, installation and performance evaluation of the new type of solar cooker.

5.1 DESIGN OF THE COOKER :

The changes which are made in the existing design are listed in 3.4.2. The tilt angle of the glass cover is decided on the basis of previous research work done on the flat plate solar collectors. It has been found that the tilt of the solar collector should be latitude plus 15° for the winter period and latitude minus 15° for the summer period [30,33,34,37]. But the same results cannot be used for the solar cooker for two reasons :

1. Above thumb rule is for the flat solar collector for long time periods of use which is not the case with the solar cooker as it is used only for small time periods.
2. Front, side and back heat loss patterns are different for solar cooker.

The tilt angle for the cooker is kept equal to the latitude of Kanpur i.e. about 29°. This angle allows increased solar radiation for all the months as well it gives sufficient space for the two extra upper vessels and also keeps the heat loss

area within limits. It has been found that front heat loss coefficient for a tilted surface is almost constant up to a tilt angle of 45° (fig. 5.1).

Front height of the absorber plate is kept equal to the height of the vessels plus some clearance. Clearance is provided for the safety of the glass cover. The dimensions of the bottom plate are kept equal to the area occupied by four vessels plus clearance.. Insulation thickness, glass cover thickness and spacing between the glass covers are all decided based on the past work on the box-type solar cooker. Effect of air thickness on the coefficient of front heat loss for a flat plate solar collector is shown in the fig. 5.2.

The material for the different components are decided on the basis of,

i. past experience with the solar cooker design and performance

ii. availability and workability of the materials.

5.2 DESCRIPTION OF THE COOKER :

The new solar cooker is a double-walled box (fig. 4.1, plates 5.1 and 5.2). The inner casing is made of aluminum sheet (0.9 mm thickness). The bottom plate has dimension 40 cm x 40 cm. The front and back side height of the inner casing are equal to 9 cm and 34 cm respectively. On all sides of the inner casing except at the cover side, insulation of 5 cm thickness is provided. Outer casing is made of galvanized iron sheet of 1 mm thickness. An iron grill is provided at a height of 10 cm above the lower vessels.

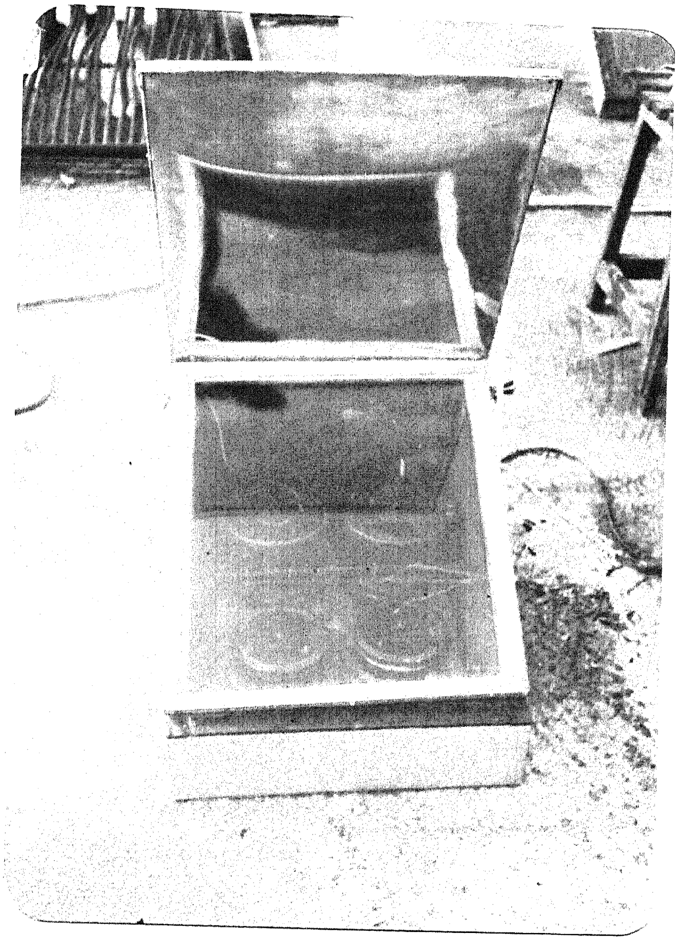


Plate 5.1 Front view of the new soalr cooker (with reflector).

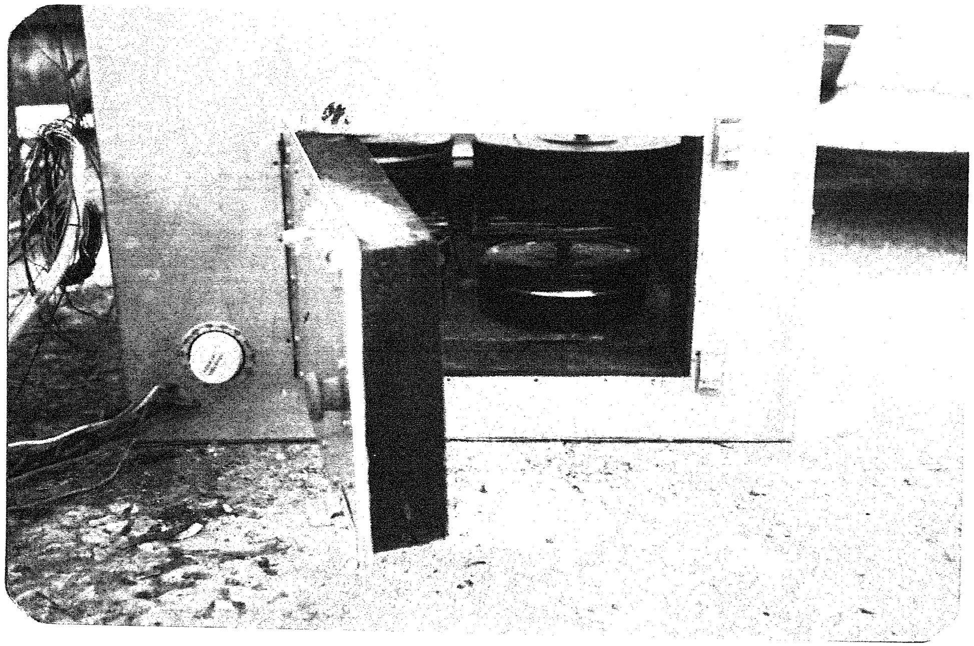


plate 5.2 Back view of the new solar cooker.

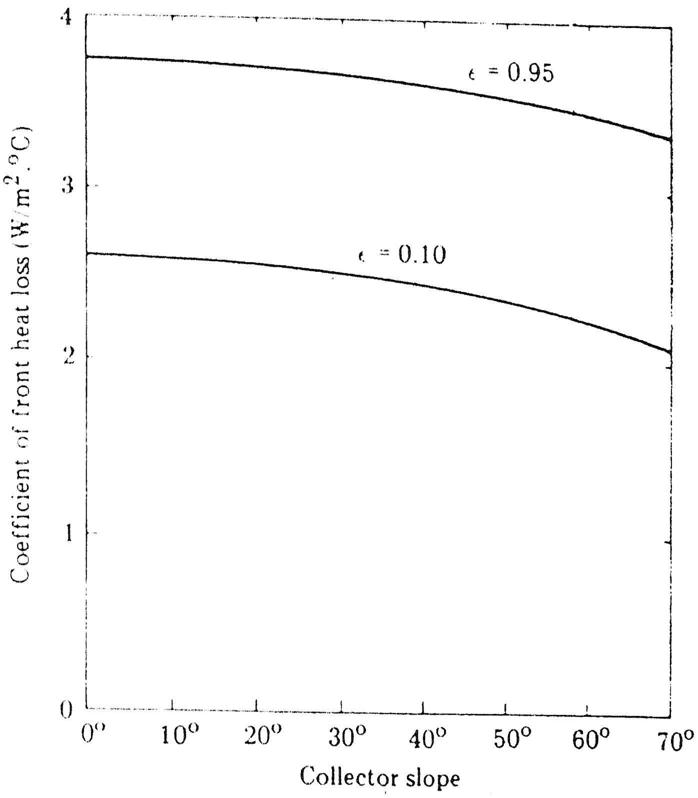


Fig. 5.1 Effect of collector slope on the coefficient of front heat loss.

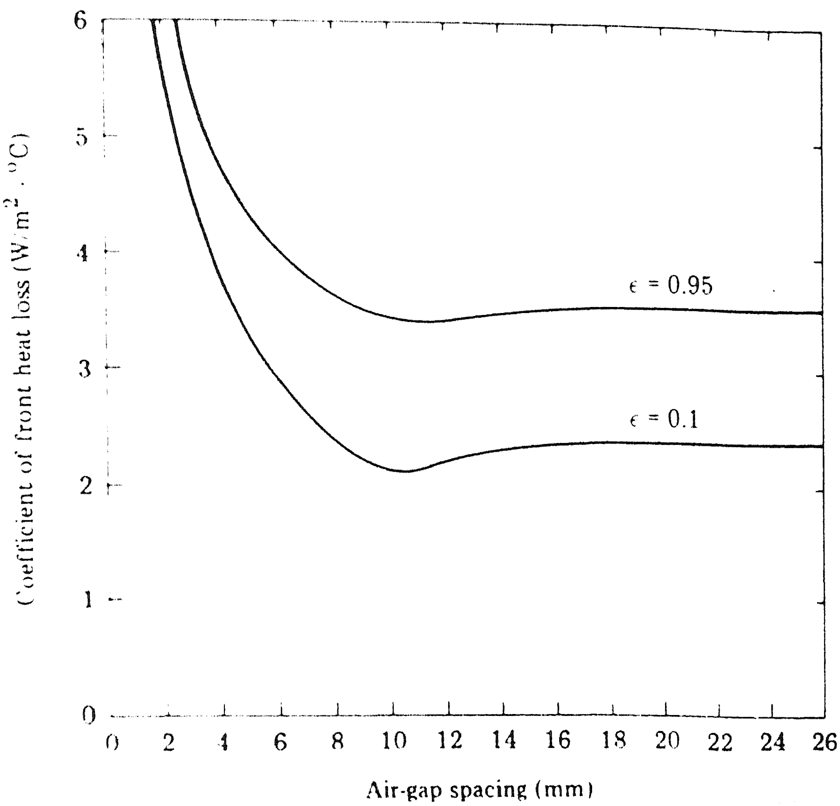


Fig. 5.2 Effect of air gap thicknes on the coefficient of front heat loss.

Glass cover consists of double glazing, each having a thickness of 4 mm and separated by a distance of 12 mm. A double walled door is provided at the back of the cooker. Pots of aluminium and stainless steel were used for the testing purpose.

5.3 FABRICATION :

The inner casing is made from a aluminium sheet of 83 cm x 108 cm x 0.9 mm. The sides of the inner casing are rivetted together using mild steel rivets. It is perfectly sealed by pressing the joints together by hammering. The outer casing is made similarly from galvanized iron sheet. The two casings are joined together by wood strips. The door is made of wood, aluminium sheet and galvanized iron sheet. Inner surface of the door is made of the aluminium sheet, outer surface is made of G.I. sheet and both of them are connected by wood blocks for thermal insulation. Inner casing, inner surface of the door and the grill are all painted black.

Glass cover system is constructed by fixing the two glasses in a frame made of aluminium angles. Wood strips are kept between them for providing the spacing and support. Sponge packing is provided wherever the glass surface rests on any other surface. The domestic hot iron heating elements are used for the purpose of heater as these are cheap and easily available. Four elements are used. These are pressed between two aluminium sheet and the sheets are rivetted together. Asbestos insulation is provided at the back of the elements while mica insulation is provided at the front side. This assembly is fixed to the bottom of the aluminium sheet

of the cooker. The lead wires are taken out from each heating element. A cover is provided at the base of the outer casing so that the heater can be removed easily for repair.

The upper sides of the inner casing and the outer casing are connected by wood strips. Thermostatic switch lead is attached to the inner casing. Heater plate is attached to the bottom plate. Lead wires are insulated by asbestos clothe. Glass wool is filled from the bottom of the cooker and the bottom plate is screwed to the base. Grill is fixed inside the inner casing by two aluminium angles. Door is fixed to the casing assembly. A latch is provided to the cooker body to keep the the door tightly closed. Rubber packing is provided at the upper surface of the casings. Glass cover system is put on this packing. The cover system is fixed to the casings by screwing the aluminium angle to the outer casing surface. Electric connections are provided for the heater and the thermostatic switch to get energy input of different capacities. Adhesive is used at all the joints to make the cooker leak proof. Thermocouples are attached to different surfaces by adhesive. Thermocouples were placed on the back plate and the bottom plate, in the air, on the outer glass cover and on the vessel covers. Location of the thermocouples on the back plate and the bottom plate are shown in the fig. 5.3.

5.4 INSTRUMENTATION :

5.4.1 TEMPERATURE MEASUREMENT :

To measure the temperature of different surfaces, 10 copper constantan thermocouples were used. These thermocouples

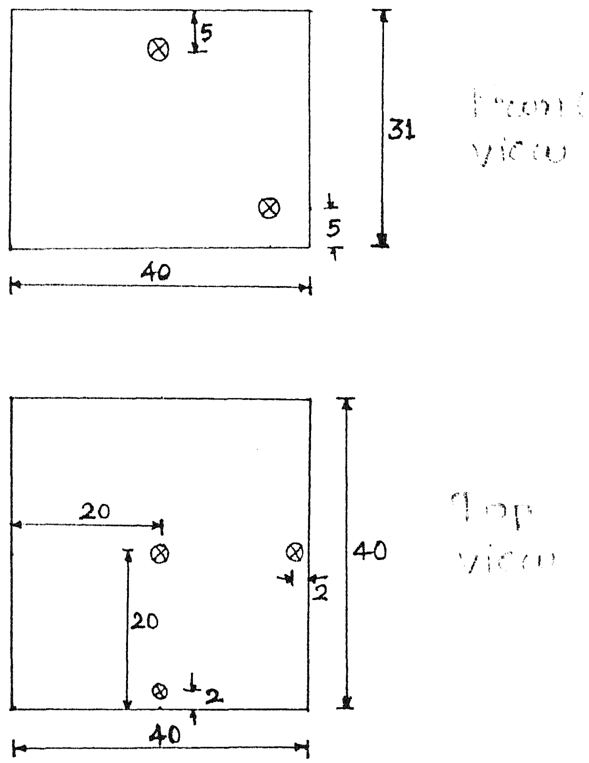


Fig. 5.3 Locations of the thermocouples

were calibrated using a silicon oil bath. The bath was heated to different temperatures and the emf generated was measured by a digital millivoltmeter. Temperature v/s emf data were plotted and equations of straight lines were obtained for each thermocouple. These equations of straight lines are used for converting the measured thermo-emf.

To get multi channel temperature measurements, one ten point rotary switch was used. This switch connects different thermocouples to the digital millivoltmeter.

At the end of the experiment the water temperature inside the vessels was measured by mercury in glass thermometer(0-120 $^{\circ}$C).

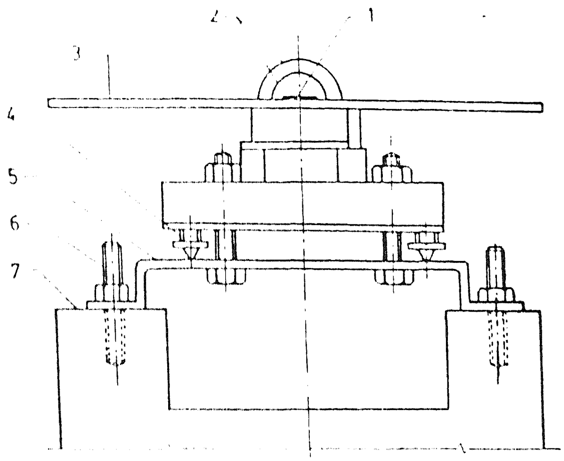
Ambient temperature and the room temperature were also measured by mercury in glass thermometer (0-120 $^{\circ}$C).

5.4.2 SOLAR RADIATION INTENSITY MEASUREMENT :

Global solar radiation was measured using a kipp and Zonen CM 5 pyranometer (fig. 5.4). It was put near the solar cooker and the leads were connected to the millivoltmeter. Thermo-emf generated is measured and is converted into the solar radiation intensity by multiplying it by the pyranometer constant.

5.5 TEST-PROCEDURE :

Circuit diagram of the experimental set-up is shown in the fig. 5.5. At the starting of the experiment, vessels were filled with the measured quantity of water. Temperature of the



1. Black surface

2. Glass domes

3. Guard plates

4. Three levelling screws

5. Mounting plates

6. Grouted bolts

7. Platform

Fig. 5.4 Pyranometer for measuring global radiation

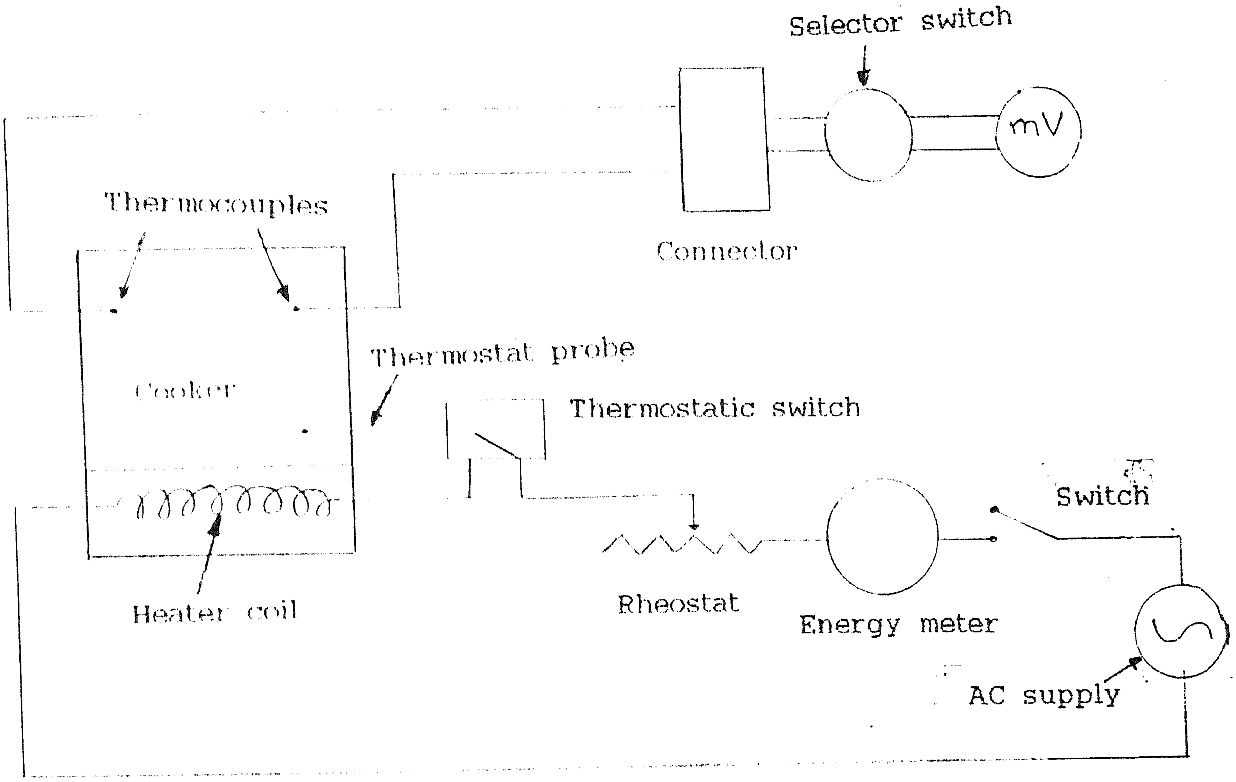


Fig. 5.5 Circuit diagram of the experimantal set-up

water was taken. Glass cover of the cooker was wiped with a clean piece of cloth. Pyranometer was put near the cooker and the leads were connected to the millivoltmeter. Thermostatic switch was set at the desired maximum temperature of the absorber plate. Temperature of the room air and the ambient air, solar radiation intensity and the temperatures of the cooker components were measured and tabulated after every 15 minutes . When heater was used, its energy input was measured using energy-meter. At the end of the experiment cooker was opened and the temperature of the water inside the vessels was measured directly using thermometer.

CHAPTER 6

RESULTS & DISCUSSIONS

The cooking operation is a transient process. The results of the experimental work and the simulation study show several features of interest.

6.1 EXPERIMENTAL RESULTS :

Experiments with different thermal loads, different arrangement of vessels, different solar radiation intensity, different amount of supplementary energy and with or without reflector and tracking have been conducted.

Figure 6.1 shows the variation in temperatures of bottom plate, vessel cover, air and global solar radiation with time, for the experiment conducted in the month of December. About 2.4 kg water was put in four vessels and the measurements were made from 10.00 am to 12.30 pm. Average global solar radiation was of the order of 550 W/m^2. Maximum temperatures attained for the vessel cover (d3), bottom plate (centre) and air (centre) are 107, 67 and 85 °C, respectively. Temperature of the water (d3) at the end of the experiment was 72 °C. A continuous rise in the temperatures is observed. The rate of temperature rise is more during the initial time period and less during the later stage. The same variation is noted for the input energy profile i.e. solar radiation intensity profile. Figures 6.31 and 6.32 show the variation of the inside

temperature of an empty solar cooker with global solar radiation and time for a box-type of solar cooker [19]. In the month of December about 95 °C is attained while the global solar radiation intensity is of the order of 690 W/m^2.

The variation in temperatures of bottom plate, vessel cover, air and global solar radiation with time, for the experiment conducted in the month of December with the additional supply of supplementary energy is shown in fig. 6.2. About 2.4 kg water was put in four vessels and the measurements were made from 3.45 pm to 5.30 pm. cooker initially hot due to first cooking performed in the forenoon. Average global solar radiation is of the order of 75 W/m^2. 0.25 kWh electric energy was supplied between 4.15 pm to 5.15 pm. Maximum temperatures attained for the vessel cover (d3), bottom plate (centre) and air (centre) are 107, 125 and 90 °C, respectively. Temperature of the water (d3) at the end of the experiment (5.30 pm) was 98 °C. After switching off the supplementary energy source a sharp fall in the bottom plate temperature profile is noted.

The variation in temperatures of bottom plate, vessel covers and global solar radiation with time, for the experiment conducted in the month of February with the additional supply of supplementary energy (225 W) are shown in fig. 6.3. About 5 kg water was put in six vessels, 2.4 kg in the lower vessels and 2.6 kg in the upper vessels. Measurements were made from 10.00 am to 12.30 pm. Average global solar radiation was of the order of 790 W/m^2. 0.28 kWh electric energy was supplied between 10.30 am to 11.45am. Maximum temperatures attained for the vessel cover (d3), vessel cover (u1) and bottom plate are 114, 110 and 116 °C,

at the top of the cooker is also almost equal to temperature of the air collected at the centre of the cooker.

figure 6.6 shows the variation in temperature of different components inside the cooker and the global solar radiation with time for the experiment conducted in the month of December (also see the fig. 6.2 and the discussion presented therein). There is considerable difference in the temperatures of the upper and lower portions of the side plate-back. The maximum temperature attained by the side plate-back-bottom and side plate-back-bottom are 101 and 86 $^{\circ}$C, respectively. Similarly there is considerable temperature gradient on the bottom plate which is mainly due to non-uniform distribution of supplementary energy. Temperature of the air collected at the top of the cooker is also more than the temperature of the air collected at the centre of the cooker.

Figures. 6.7, 6.8 and 6.9 illustrate the effect of arrangement of pots and the thermal load on the temperature profile of the vessel. There was considerable difference in the environmental conditions and the global solar radiation for different experiments. The vessel temperature profiles for 6 pot and 4 pot arrangement is presented in fig. 6.7. For the 5 pots set-up and the 4 pot set-up the average global solar radiation is of the order of 605 and 650 W/m^2 respectively. The maximum temperatures attained by the lower vessels in the 6 pot set-up and the 4 pot set-up are 80 and 95 $^{\circ}$C, respectively.The maximum temperatures attained by the upper vessels in the 6 pot set-up and the 4 pot set-up are 79 and 108 $^{\circ}$C, respectively. On the other hand the vessel temperature profiles for two arrangements of 4 pots is shown in fig. 6.8 In the arrangement 1 , 4 pots were kept

on the bottom plate and in the arrangement 2 pots were put on the bottom plate and two pots were put on the grill. In the arrangements 1 and 2 the average global solar radiation was of the order of 525 and 650 W/m^2. The maximum temperatures attained by the lower vessels in the arrangements 1 and 2 are 104 and 89 $^{\circ}C$, respectively. The maximum temperatures attained by the upper vessels for the arrangement 2 is 105 $^{\circ}C$. Vessel temperature profiles for 4 pots and 2 pots arrangement can be seen in fig. 6.9. For the 4 pots set-up and the 2 pots set-up the average global solar radiation is of the order of 530 and 520 W/m^2. The maximum temperature attained by the vessels in both the set-ups is about 103 $^{\circ}C$.

Figures 6.10 and 6.11 demonstrates the effect of tracking and reflector on the vessel temperature profiles. Three cases are considered. In the case 1, solar cooking without the use of tracking, reflector and heater is considered. In the case 2, cooker was tracked after every 30 minutes. In the case 3, cooker was tracked after every 30 minutes as well as the aluminum reflector was also used. Average global solar radiation in the three cases was of the order of 645, 660 and 560 W/m^2, respectively. Maximum temperature attained by the lower vessels in the three cases is about 95 $^{\circ}C$. Maximum temperature attained by the upper vessels in the three cases is about 92, 94 and 86 $^{\circ}C$.

The performance of the solar cooker with different amount of supplementary energy are presented in figs. 6.12 and 6.13. Three cases are considered. In case I only solar energy is used, in case II 70 W heater is used for 2 h and finally in the case III 225 W heater is used for 1.15 h. Average global solar radiation

in the three cases was of the order of 680, 670 and 760 W/m^2, respectively. Maximum temperature attained by the lower vessels in the three cases is 86, 110 and 117 °C. Maximum temperature attained by the upper vessels in the three cases is about 80, 103 and 114 °C.

An approximate cost of the new cooker is given in the table 6.1. It is to be noted in the present study the materials were selected such that they can be fabricated easily.

Comparison of the experimental results obtained for the new design with that for the other types of solar cookers is presented in the table 6.2.

6.2 COMPARISON OF COMPUTATIONAL AND EXPERIMENTAL RESULTS :

The temperature profiles for the different components of the cooker obtained by computation and experiment are presented in figs. 6.14 - 6.16. Five kg of water is heated in six vessels, 2.4 kg in the lower vessels and 2.6 kg in the upper vessels. Average global solar radiation is about 650 W/m^2. Figure 6.14 shows the temperature profiles for the upper and lower vessels. From the experimental results it is found that the maximum temperatures attained by the upper and the lower vessels are 94 and 92 °C, respectively. While computationally obtained temperatures are 118 and 93 °C respectively. Similarly the maximum temperature for the air at the centre of the cooker and the bottom plate based on the experiment and computation are 78° and 112 and 126 °C respectively. Figure6.16 shows the temperature profiles for the upper and lower portions of the side plate-back. From the

Table 6.1

COST ANALYSIS

Material	Quantity	Approx. Cost
Aluminium sheet	$1.40 \times .40\ m^2$	150
Iron sheet	$1.80 \times .50\ m^2$	100
Glass wool	$0.028\ m^3$	50
Glass	$2 \times (.57 \times .40)\ m^2$	100
Wood	$10 \times 3 \times 50\ m^2$	50
Al. angle	.250 m	80
Grill	$.22 \times .40\ m^2$	25
Vessels	6	140
Thermostat switch	1	30
Heater coil	1	15
Conductor insulator	1	15
Packing, nuts & bolts rivettes etc.	——	15
Fabrication cost	——	200
Total cost	——	970

Table 6.2

Comparision of different solar cookers

Cooker type	Water mass (kg)	Temperature (K) upper vessel	lower vessel	bottom plate	Fig. No.	Solar intensity (W/m^2)	Supplementary energy (kWh)
Mina	0.45	---	100	---	---	696	0.0
Hot-box	1.00	---	100	---	---	---	0.0
New	2.4	---	72	---	6.1	550	0.0
New	2.4	---	98	125	6.2	745	0.25
New	5.0	98	99	116	6.3	790	0.28

experimental results it is found that the maximum temperatures attained by the upper and lower portions of the side plate-back are 99 and 72 °C, respectively. While computed temperatures are 126 and 112 °C respectively. The temperatures for the upper and lower vessels when the supplementary energy was used at the rate of 70 W. From the experimental results it is found that the maximum temperatures attained by the upper and the lower vessels are 104 and 103 °C, respectively. While computed temperatures are 148 and 103 °C, respectively.

Temperatures of the vessels obtained are almost linear in both the cases. However, for the experimental results, the temperature profiles tends to flatten at higher temperature. This could be due to the increase in air temperature inside the cooker to a limit , carrying with it valuable energy. Thus losses increases and the temperature curve tends to flatten. Further the actual experimental set-up is different in many respects from the stimulated system because all surfaces are assumed to be smooth and straight which is not so in fabricated unit.Presence of holes drilled for the insertion of thermocouples makes it very difficult to keep the cooker airtight. Contact resistance between the vessels and the absorber plate, heat transfer from the vessel cover to the vessel contents, heat transfer to the upper vessels, shadow effect of the vessels on the different components lead to difficulty in exact to prediction of temperatures.exactly. Nevertheless computed results predict higher values of temperatures which is obvious because it is not possible to include all sources of heat loss as occurring across the insulated chamber in a physical model.

6.3 COMPUTED RESULTS :

Computer simulation work is done for the cooker loaded with 6 pots and 5 kg of water. Some parameters used for the simulation purpose are given in the appendix D.

Figures 6.18 to 6.22 shows the effect of supply of different amount of supplementary energy on the temperature response of the vessel contents. For the continuous supply of 125 W, maximum temperatures attained in the upper and the lower vessels are 110 and 178 $^{\circ}$C, respectively. For the continuous supply of 75 W electric heating energy, maximum temperatures attained in the upper and the lower vessels are 146 and 96 $^{\circ}$C. For the supply of 125 W electric heating energy for one hour, maximum temperatures attained in the upper and the lower vessels are 92 and 128 $^{\circ}$C. For the supply of 75 W electric heating energy for one hr, maximum temperatures attained in the upper and the lower vessels are 86 and 119 $^{\circ}$C. With the supply of 500 W, 100 $^{\circ}$C in the lower pot is reached in about 30 minutes. While with the supply of 100 W, 100 $^{\circ}$C in the lower pot is reached in about 80 minutes. There is a marked change in the temperature profiles of the lower vessels after the removal of the supplementary energy source. But the temperature of the upper vessel is found to be increasing continuously as all other components around these are at higher temperatures. Due to less heat transfer to the upper vessels, low temperatures are attained therein.

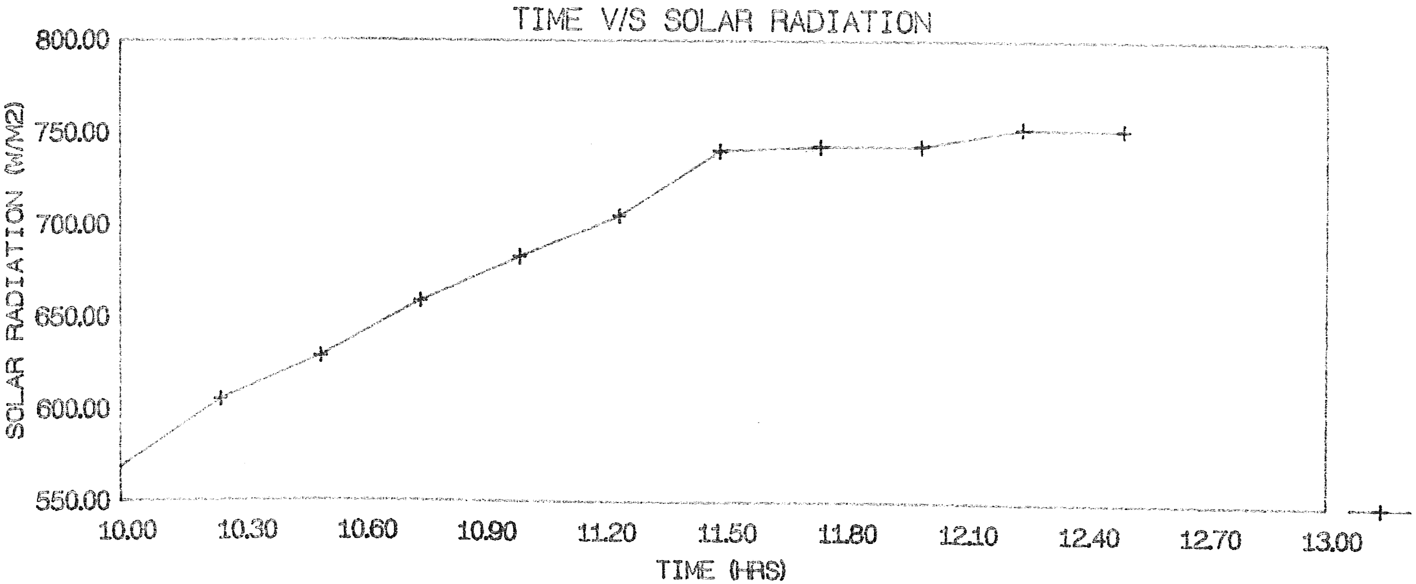
Figure 6.23 shows the variation of time required to reach 100 $^{\circ}$C in the lower vessel with the absorber plate

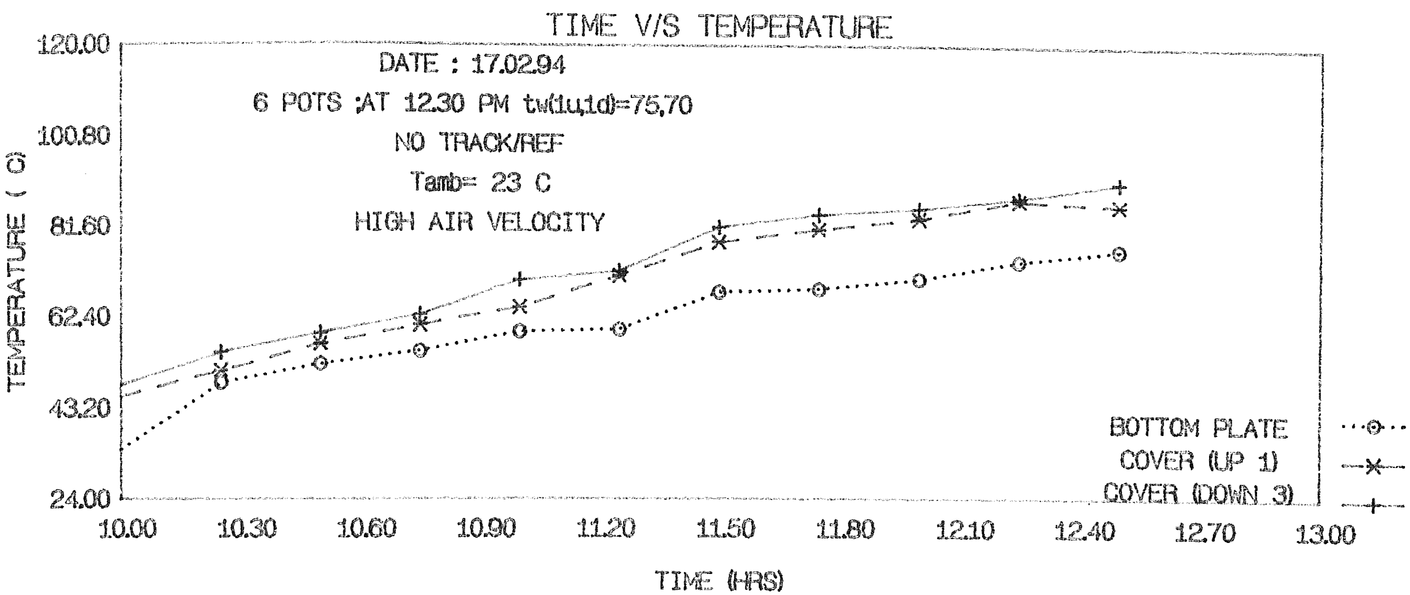
thickness. Fig. 6.24 shows the variation of time required to reach 100 °C in the lower vessel with the vessel thickness.
Fig. 6.25 shows the variation of time required to reach 100 °C in the lower vessel with the insulation thickness. For the insulation thickness below 60 mm there is a steep rise in the value of time required to reach 100 °C.

The heat loss from the sides of the cooker during the whole time period is shown in figs. 6.26 and 6.27 and the variation of heat loss from the different sides of the cooker is shown in fig. 6.27 with 70 W. Heat loss from the bottom plate is maximum.

Figure 6.27 shows the variation of heat loss by various modes with time when electric heater (70 W) is used. Heat loss by radiation from the front side is more than the heat loss from the sides of the cooker for the initial time period while during the later period heat loss from the sides is more.

Figs. 6.29 and 6.30 show the variation of temperatures of the vessels with time for two sizes of the cooker and with or without heater. For the cooker of 8 times larger than the normal size cooker, maximum temperatures attained in the upper and lower vessels are 55 and 89 °C, respectively. When 375 W of supplementary energy is used,maximum temperatures attained are 64 and 114 °C. When 500 W of supplementary energy is used,maximum temperature attained in the lower vessel is 128 °C. The bigger cooker has a collection area, four times the collection area for the smaller cooker. While the bigger cooker has a thermal mass eight times the thermal mass for the smaller cooker. Hence the collected energy per unit thermal mass for the smaller cooker is two times that for the bigger cooker. But at the same time the heat loss area per unit thermal mass is twice for the smaller





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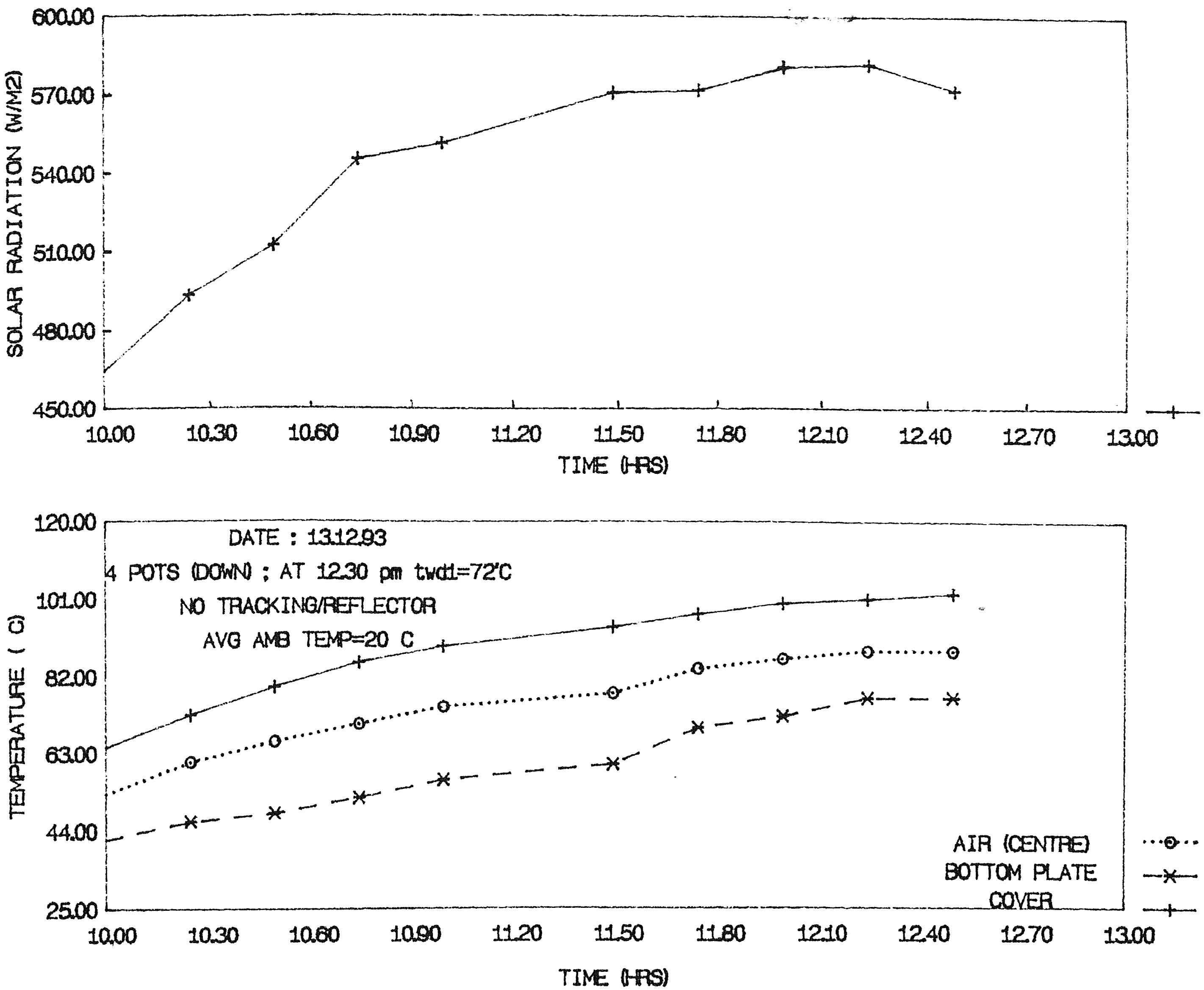


Fig. 6.1 Variation of temperatures of the cooker components and global solar radiation with time (4-Pots, Dec.)

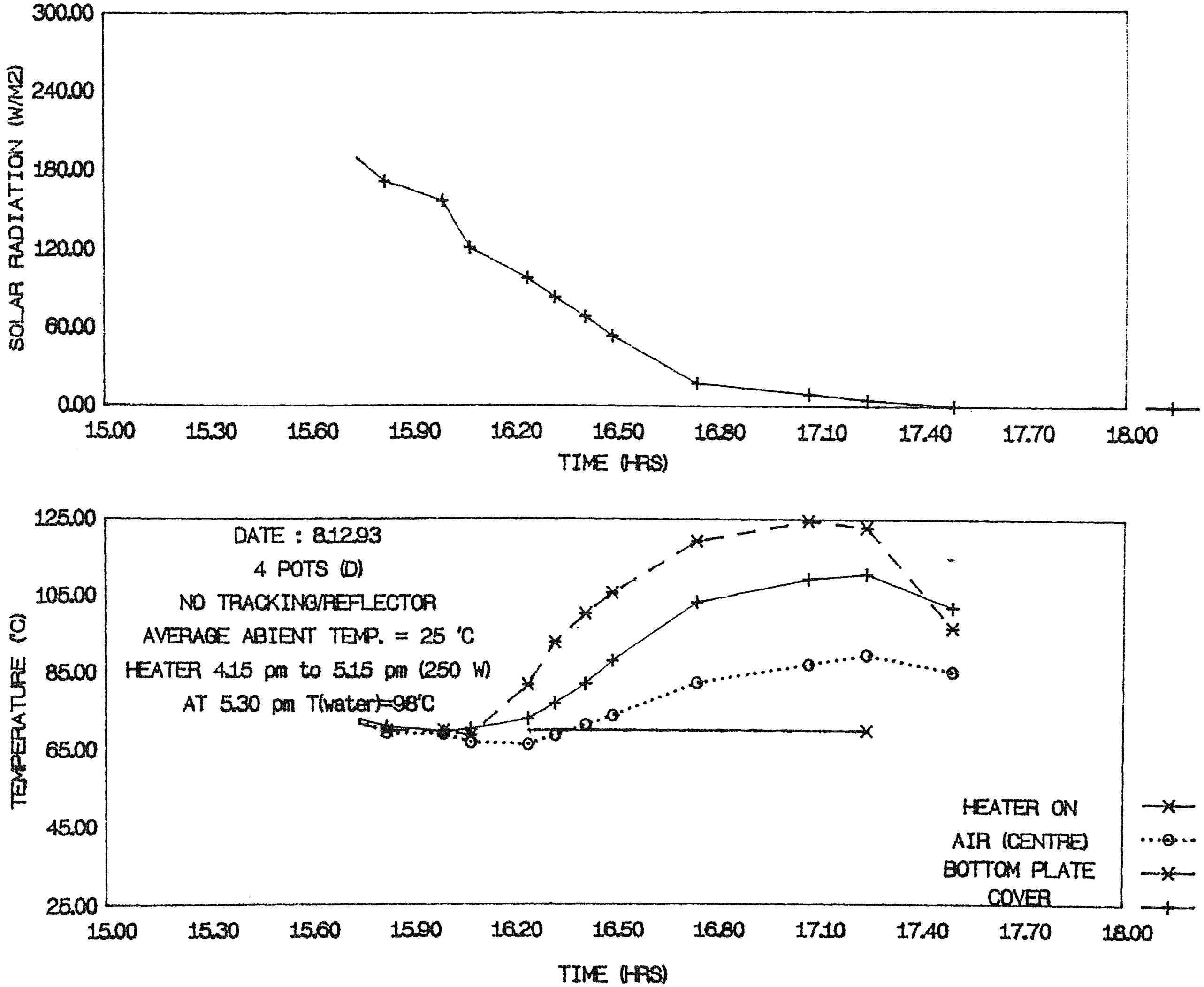


Fig. 6.2 Variation of temperatures of the cooker components and global solar radiation with time (4 Pots, Dec.,250 W)

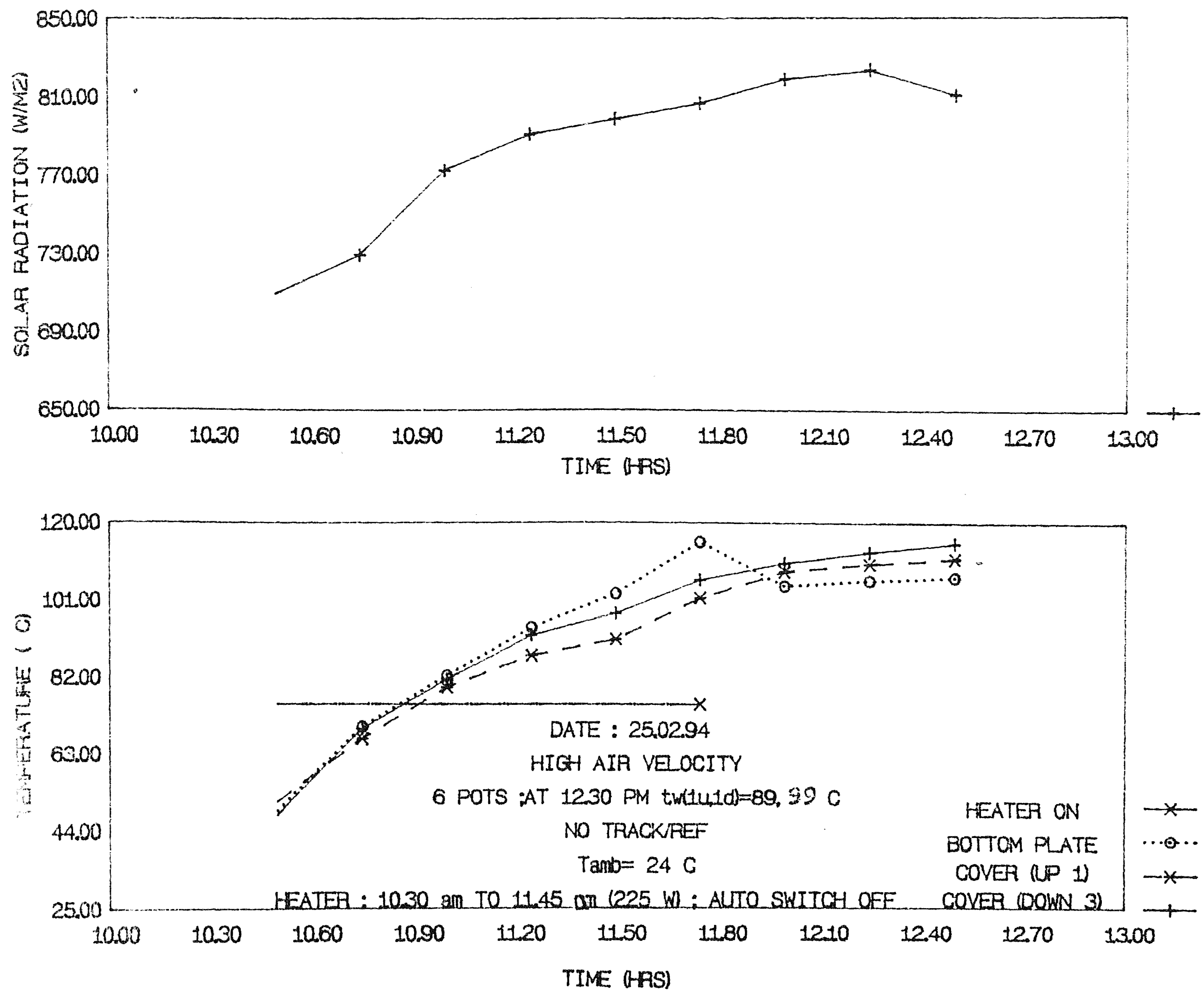


Fig. 6.3 Variation of temperatures of the cooker components and global solar radiation with time (6 Pots, Feb., 225 W)

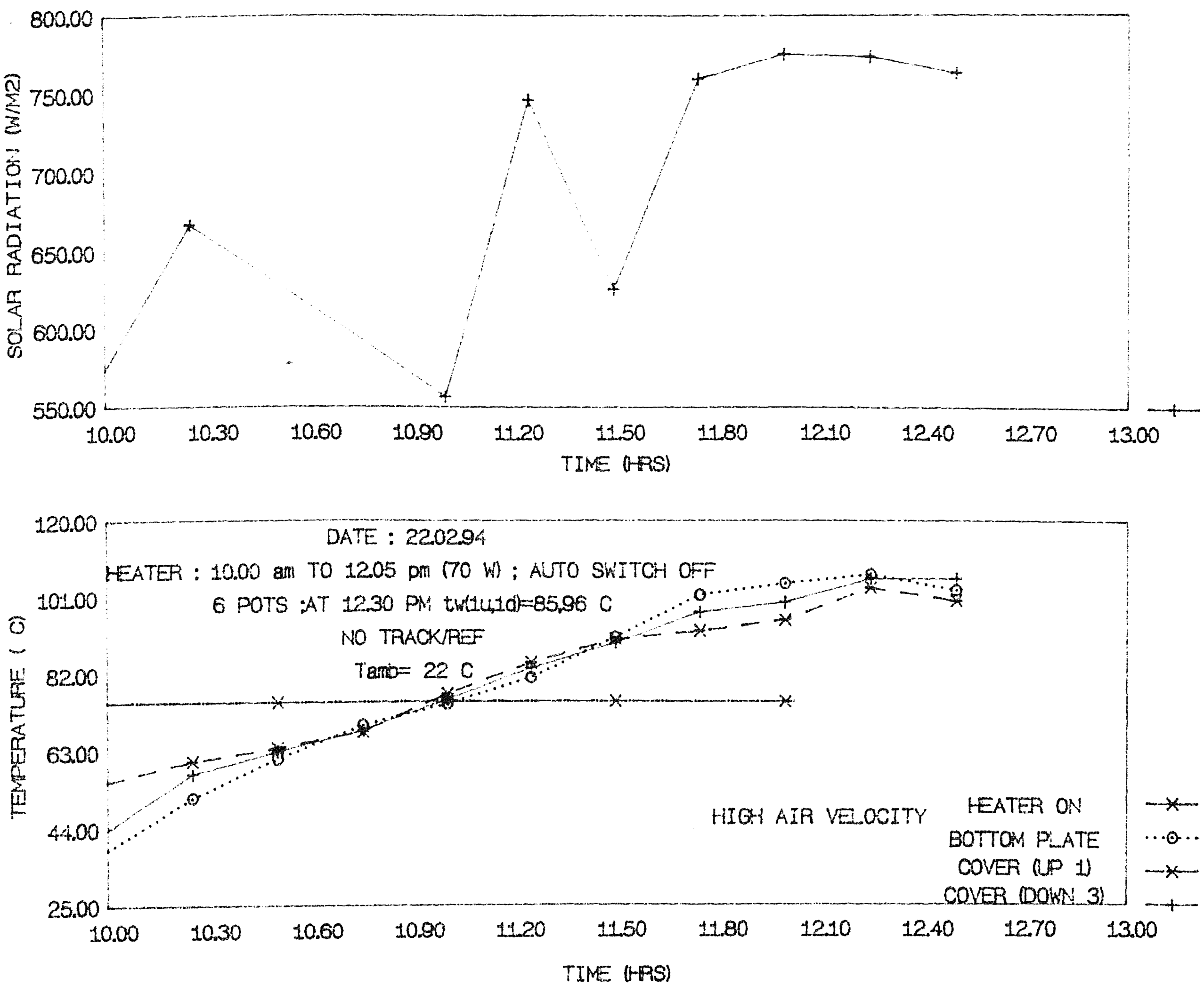


Fig. 6.4 Variation of temperatures of the cooker components and global solar radiation with time (6 Pots, Feb.,225 W)

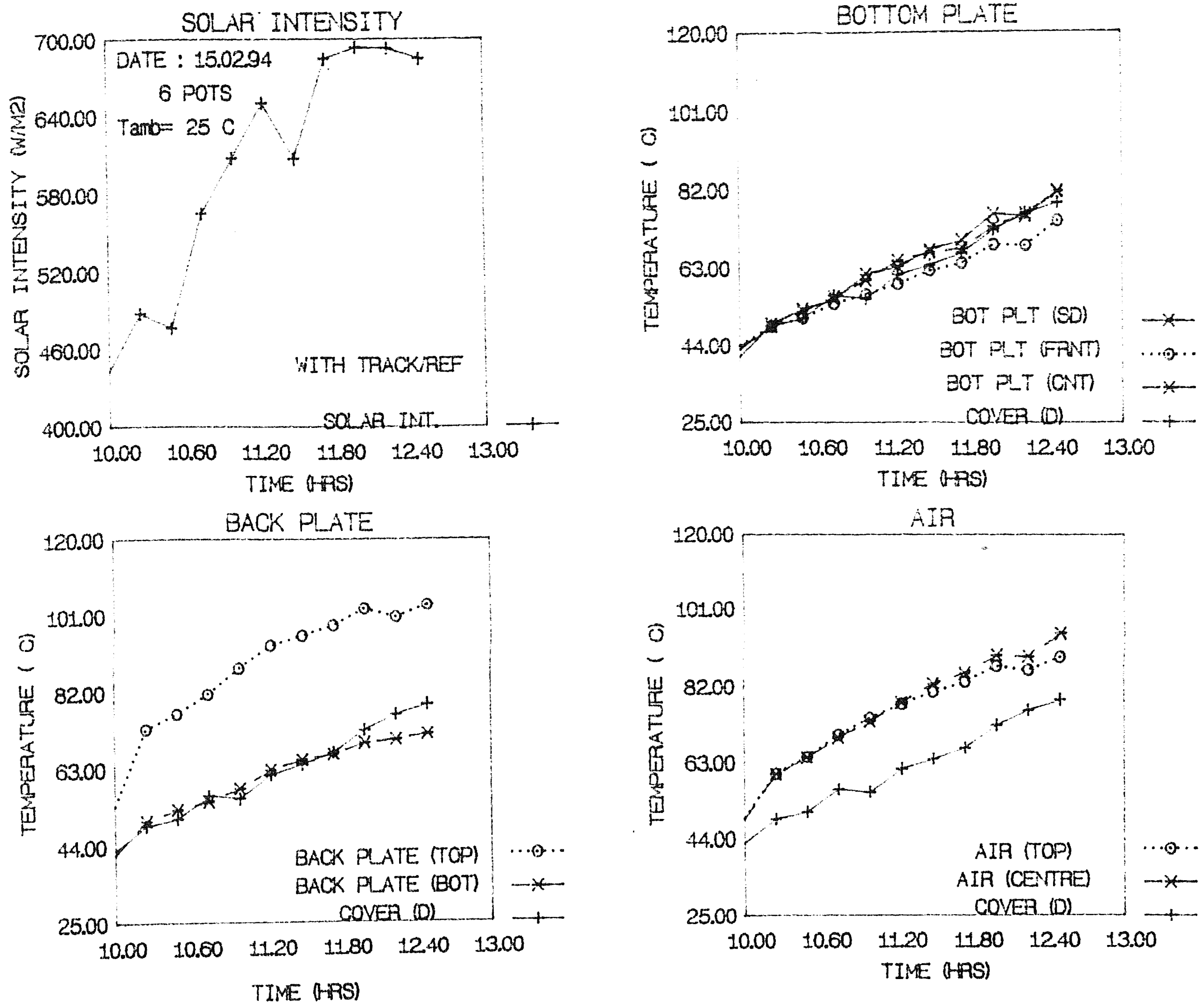
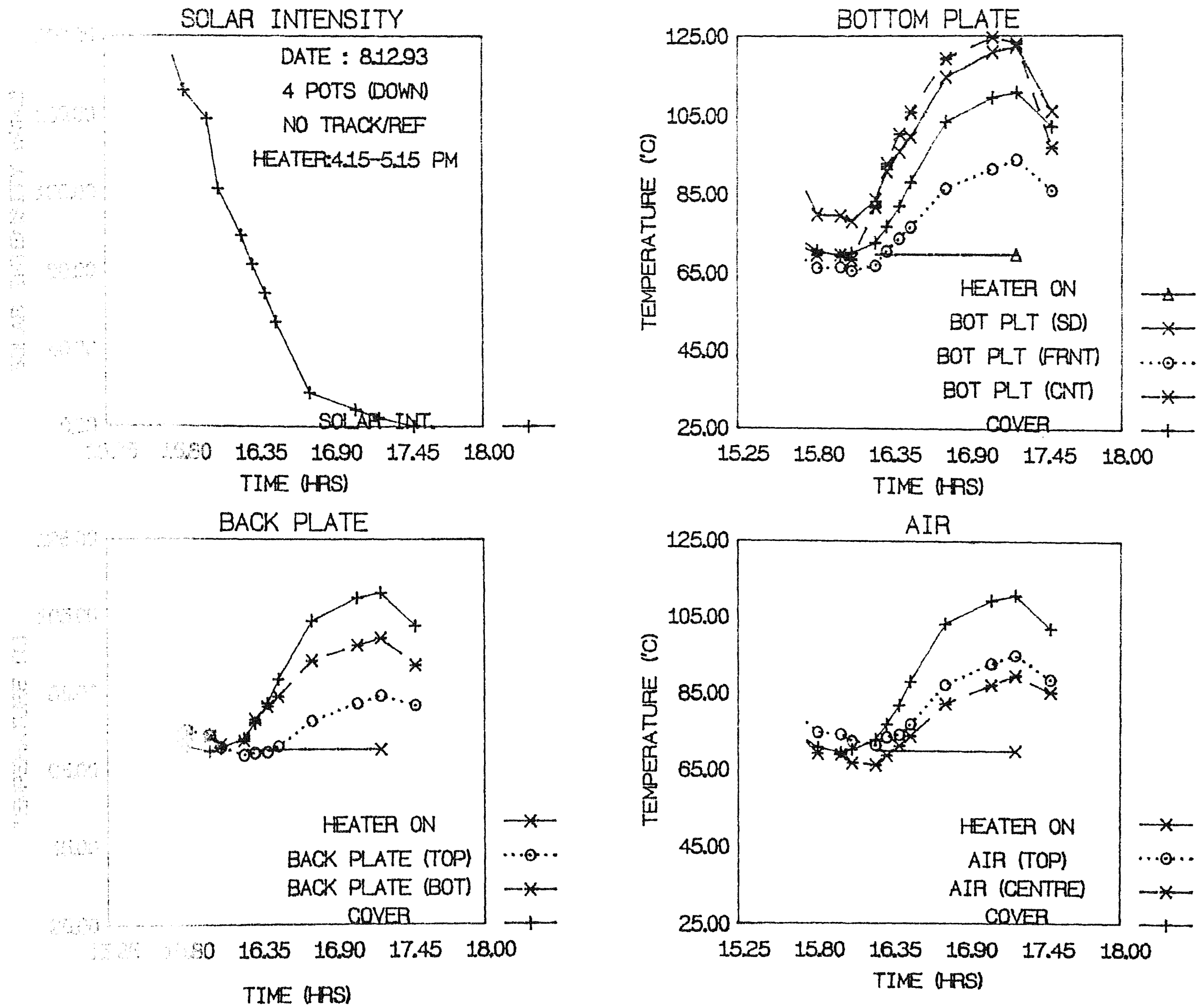


Fig. 6.5 Variation of temperatures of the cooker components and global solar radiation with time (6 Pots, Feb.)



Variation of temperatures of the cooker components and global solar radiation with time (4 Pots, Dec., 250 W)

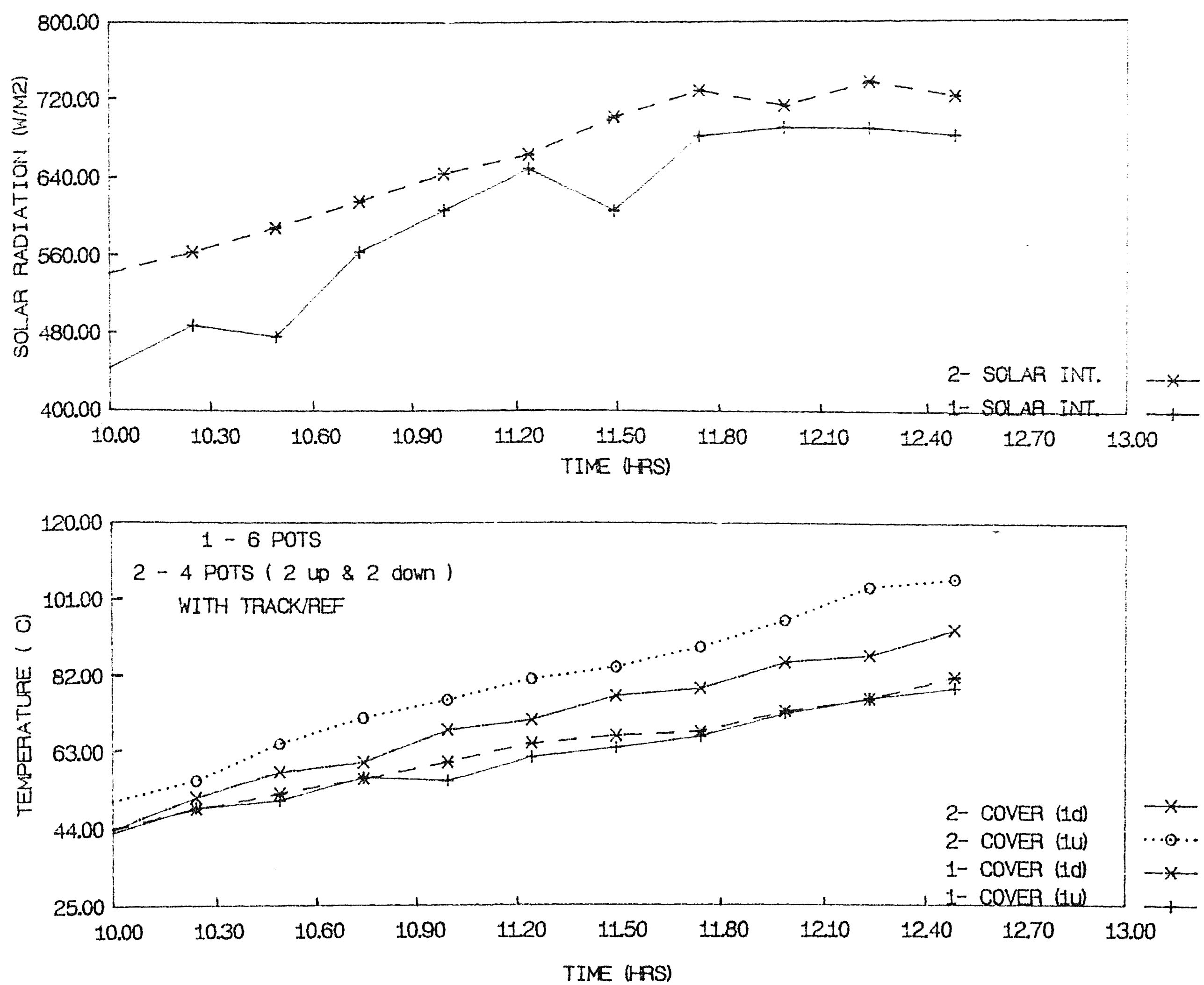


Fig. 6.7 Variation of temperatures of the vessels and global solar radiation with time (6 v/s 4 Pots)

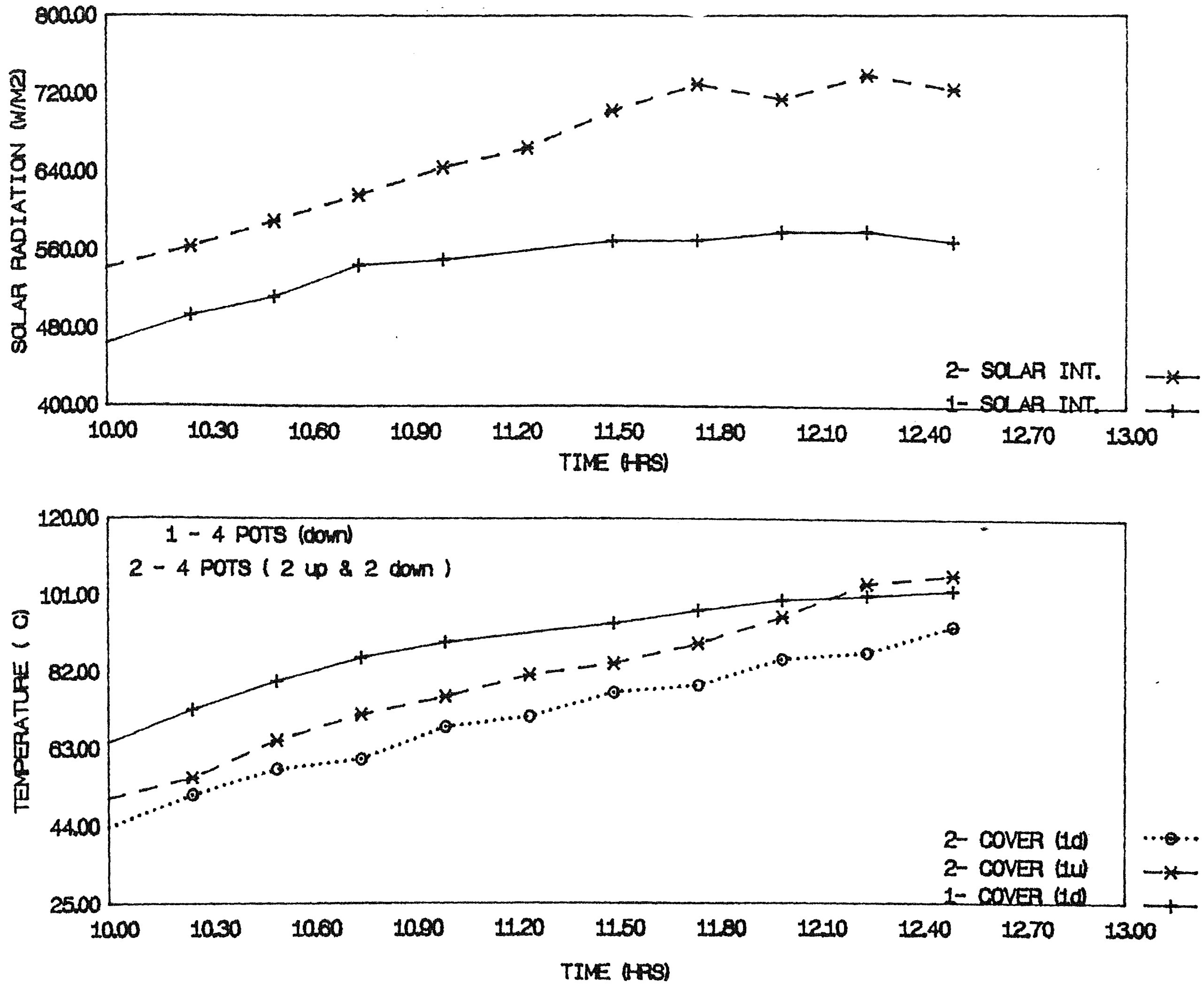


Fig. 6.8 Variation of temperatures of the vessels and global solar radiation with time (4 v/s 4 Pots)

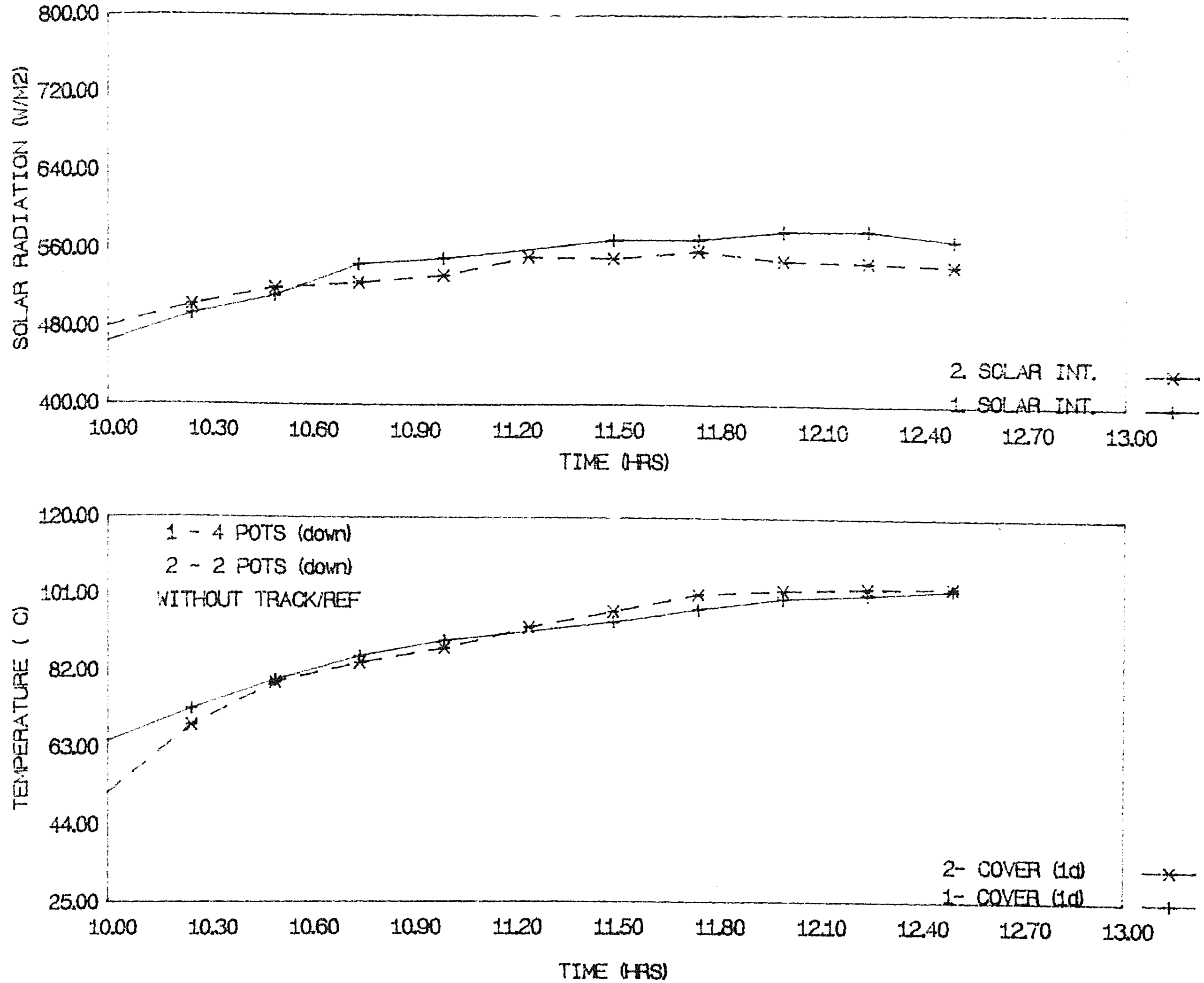


Fig. 6.9 Variation of temperatures of the vessels and global solar radiation with time (4 v/s 2 Pots)

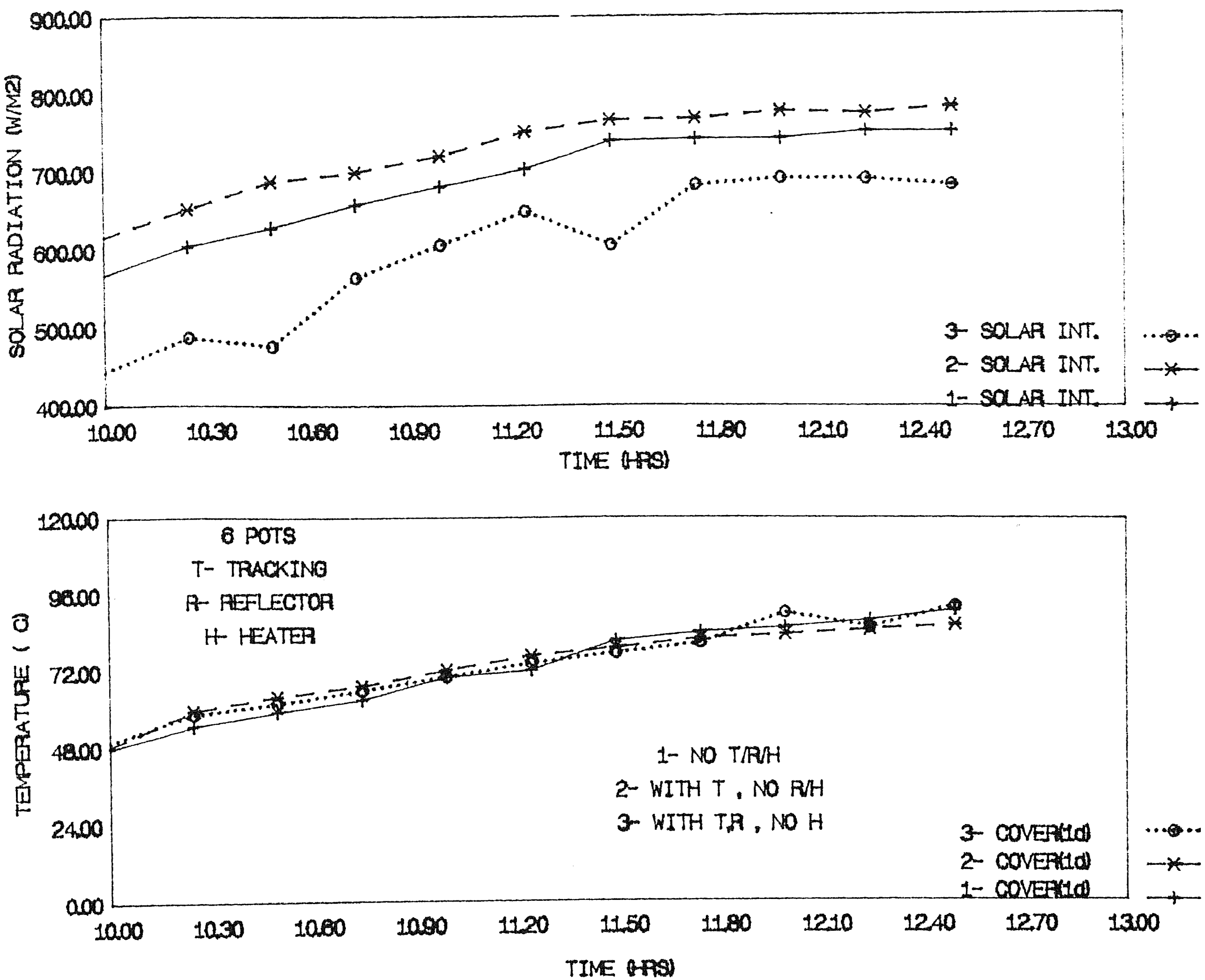


Fig. 6.10 Variation of temperatures of the lower vessels and global solar radiation with time (tracking and reflector)

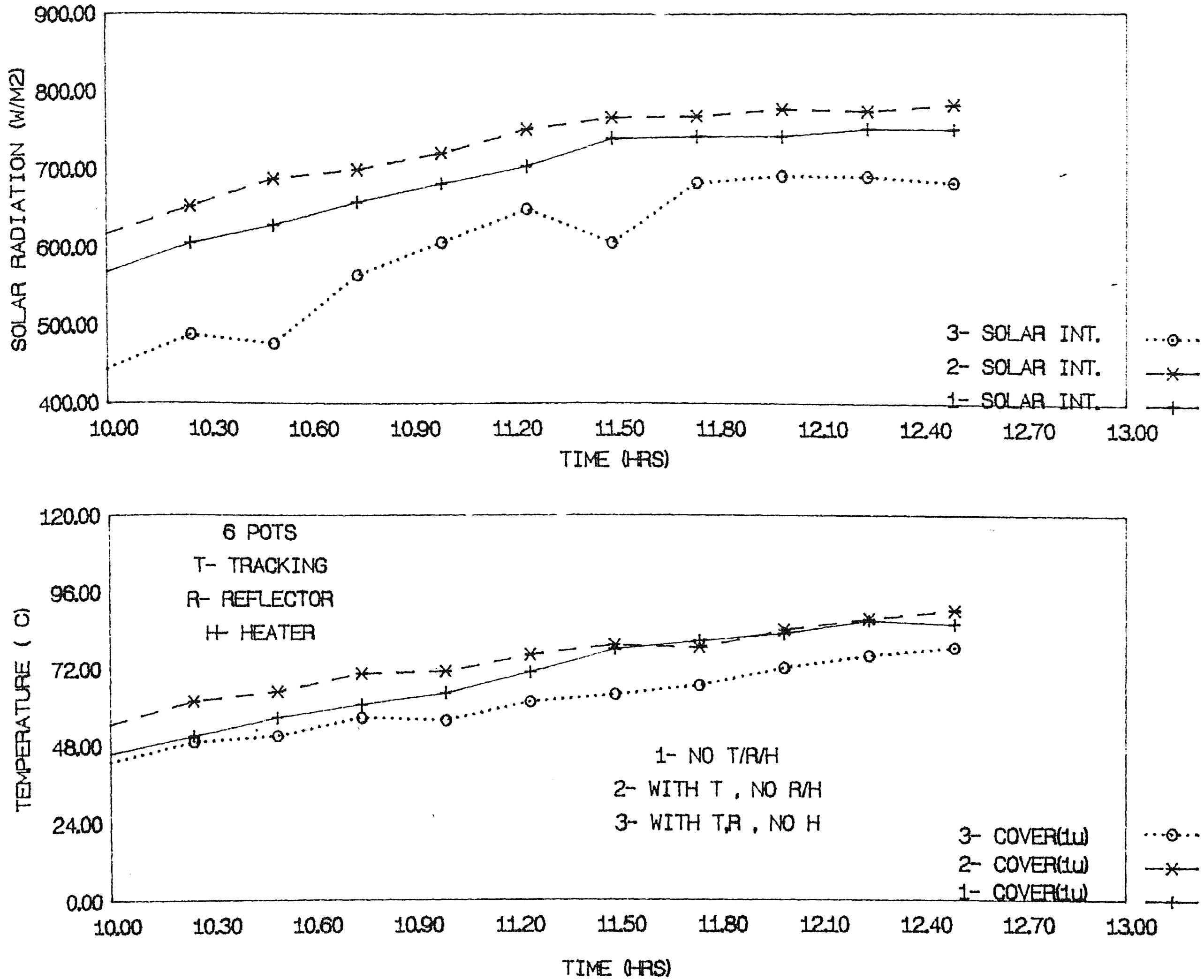


Fig. 6.11 Variation of temperatures of the upper vessels and global solar radiation with time (tracking and reflector)

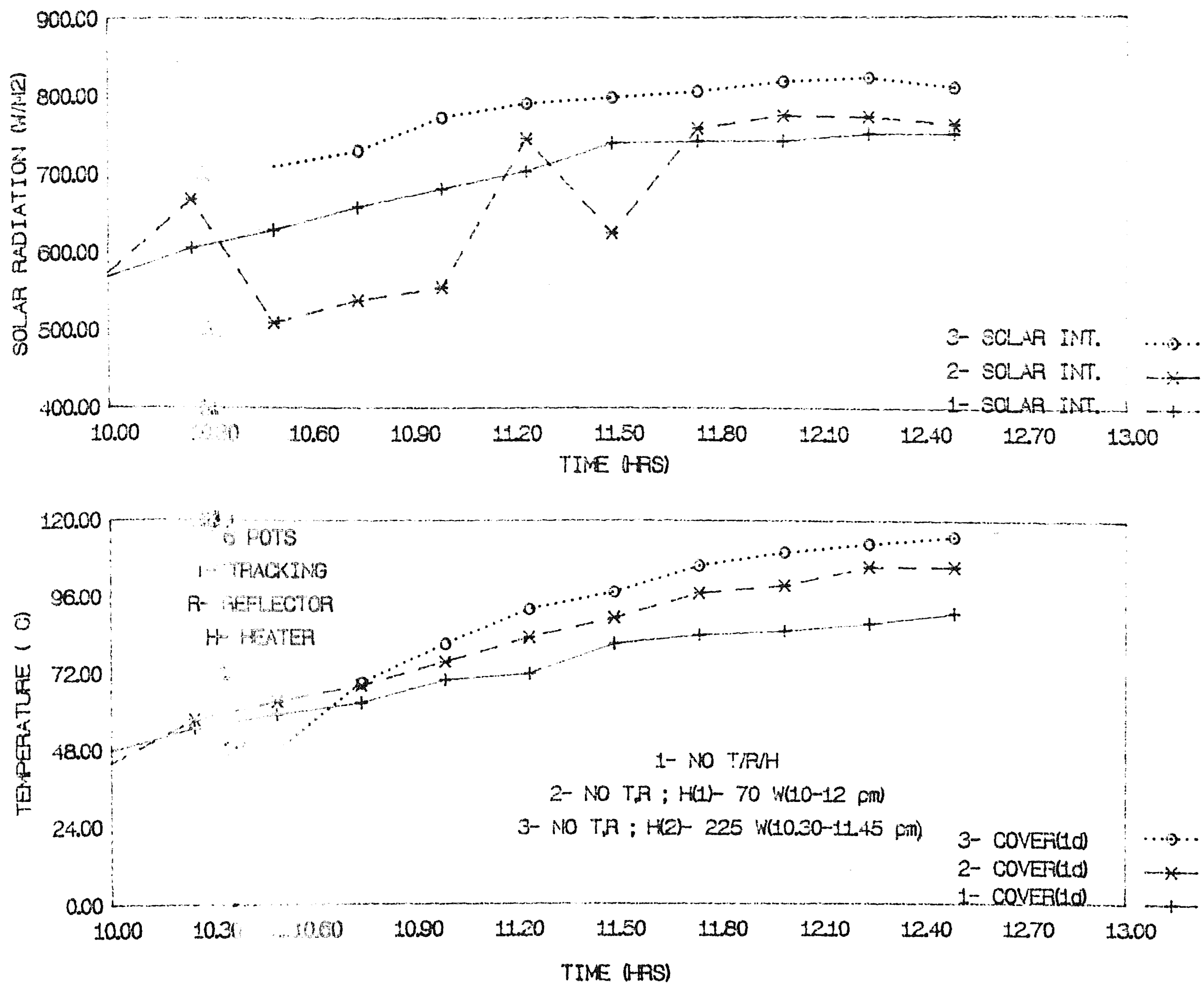


Fig. 6.12 Variation of temperatures of the lower vessels and global solar radiation with time (heater 70 and 225 W)

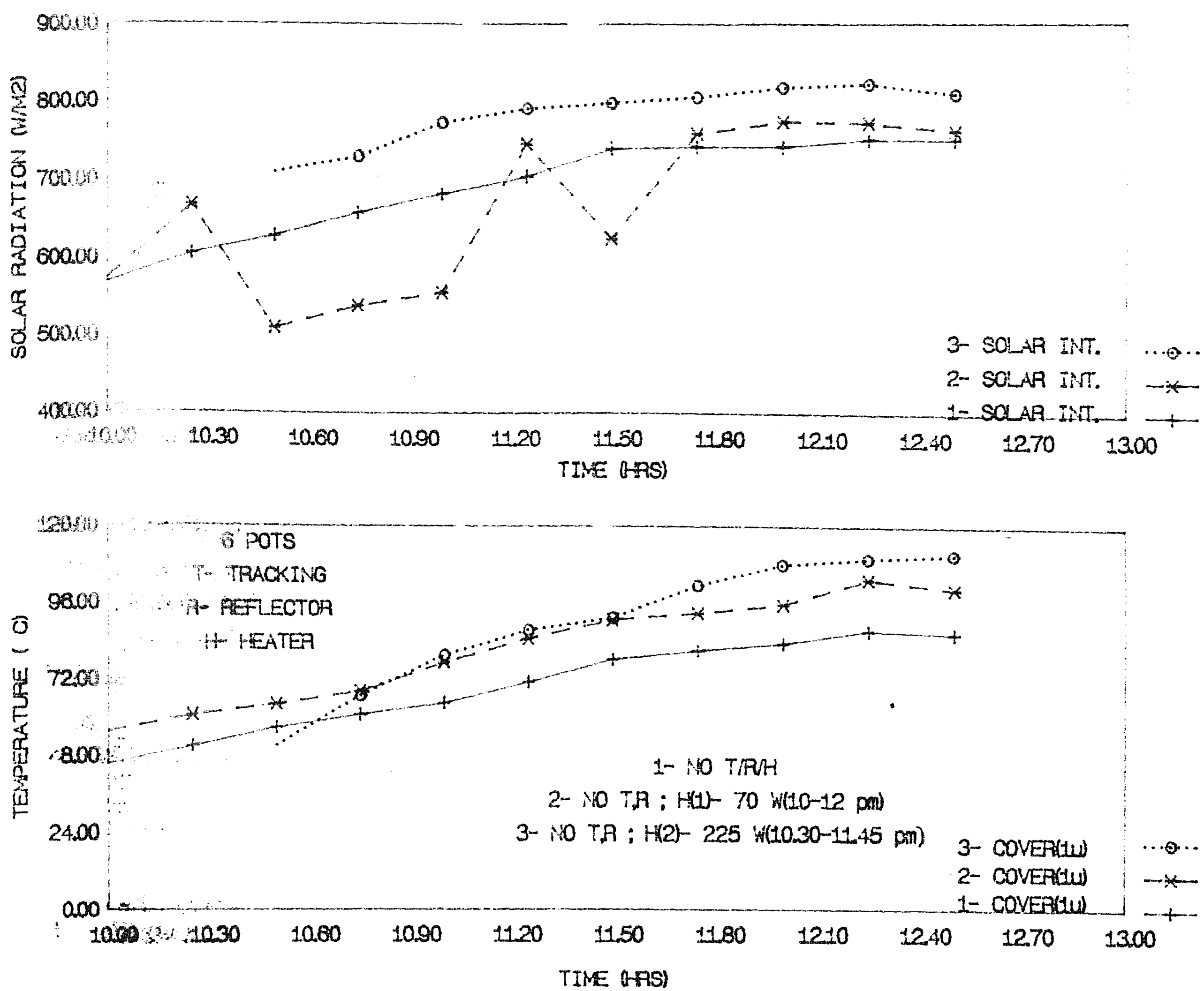


Fig. 6.13: Variation of temperatures of the upper vessels and global solar radiation with time (heater 70 and 225 W)

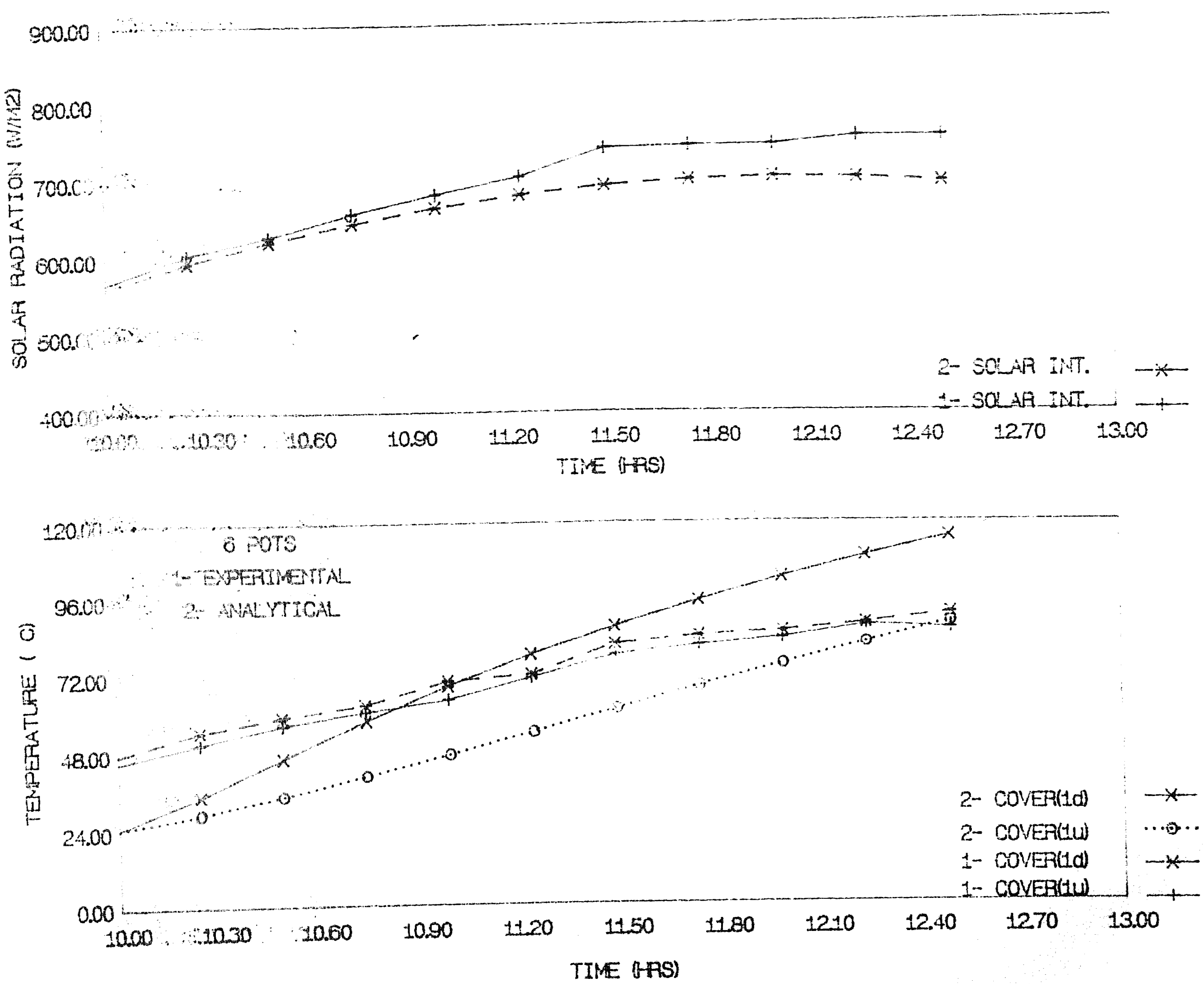


Fig. 6.14 Comparison of computational and experimental results

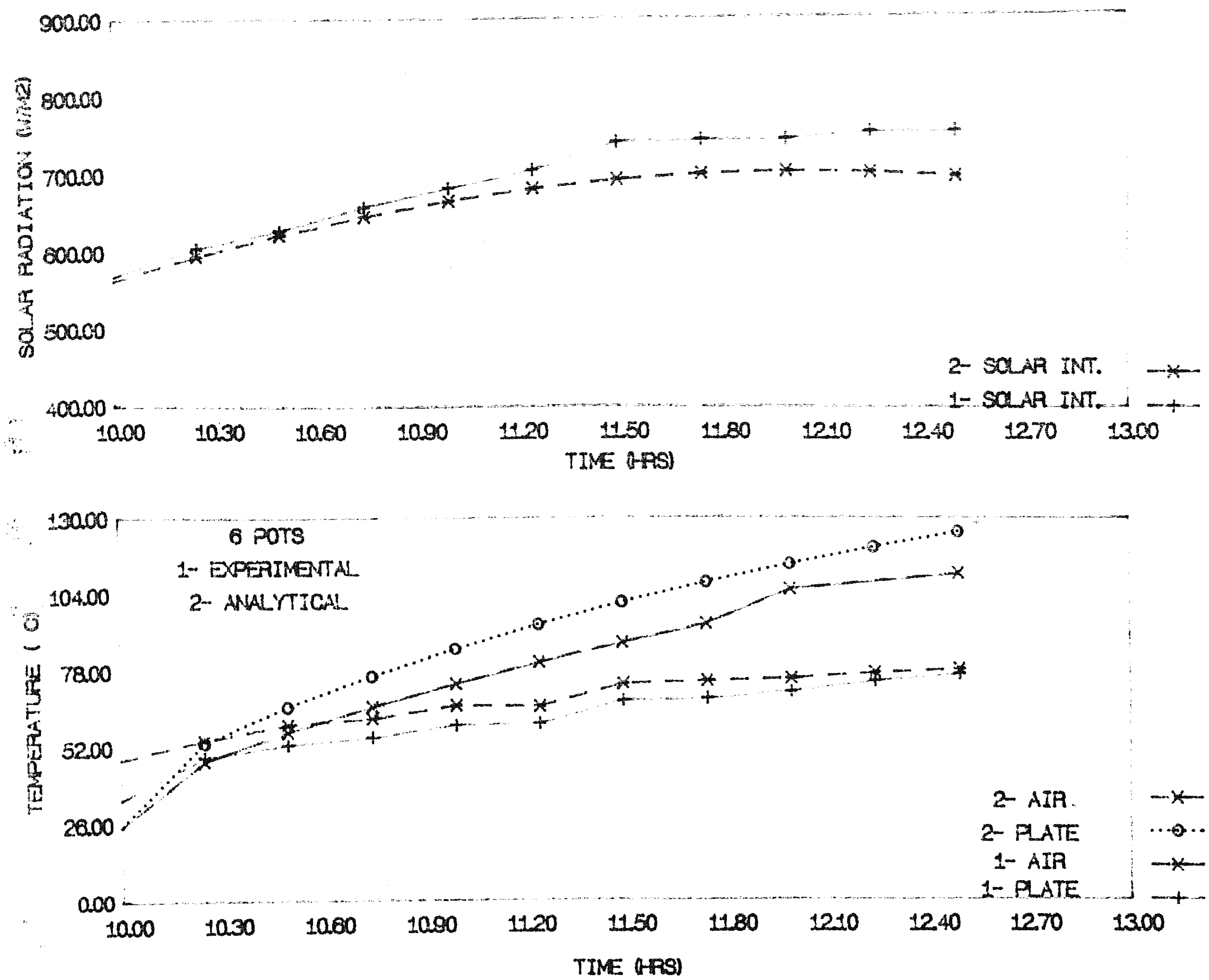


Fig. 6.15 Comparison of computational and experimental results (Air and Plate)

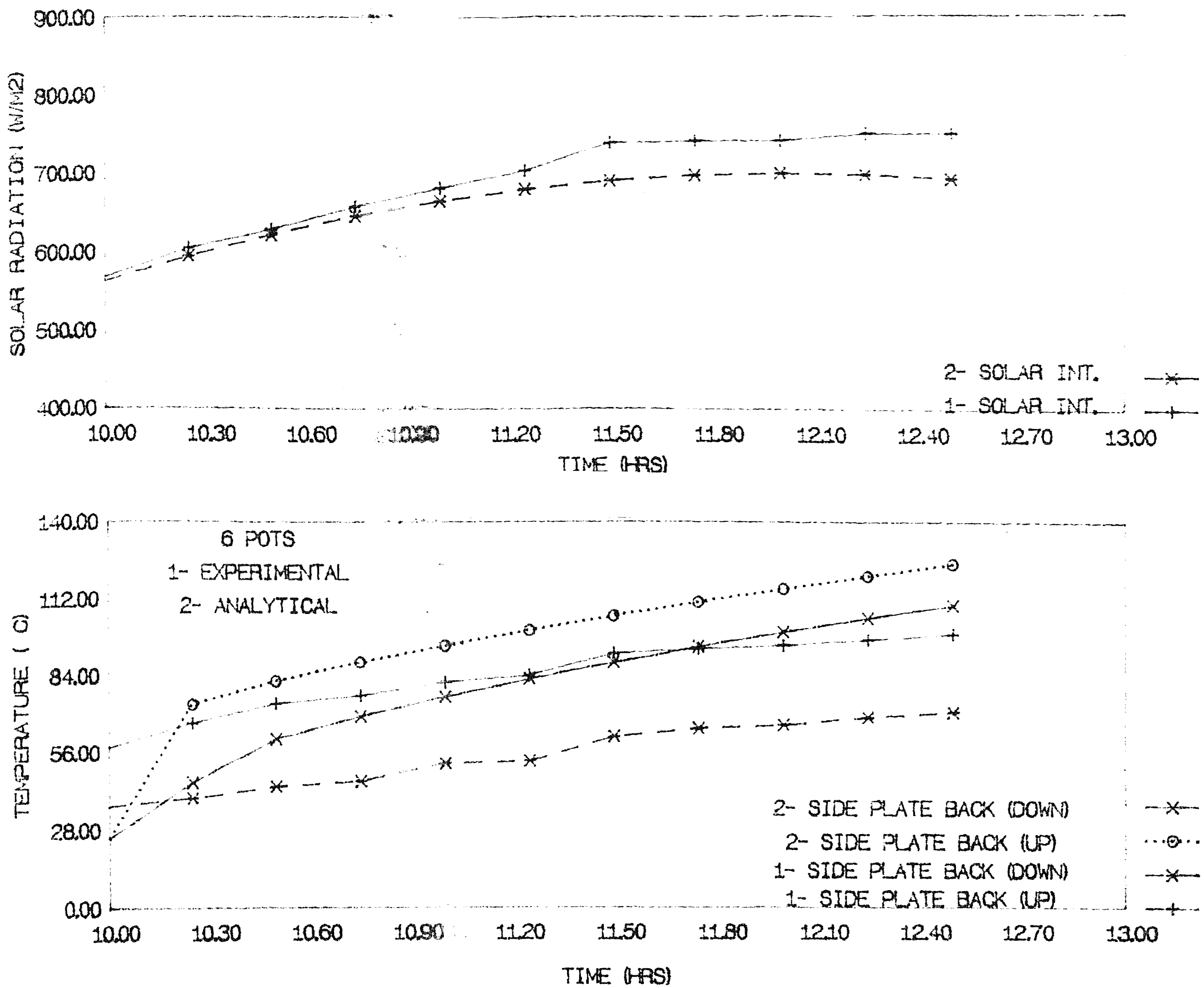


Fig. 6.16 Comparison of computational and experimental results (Back plate)

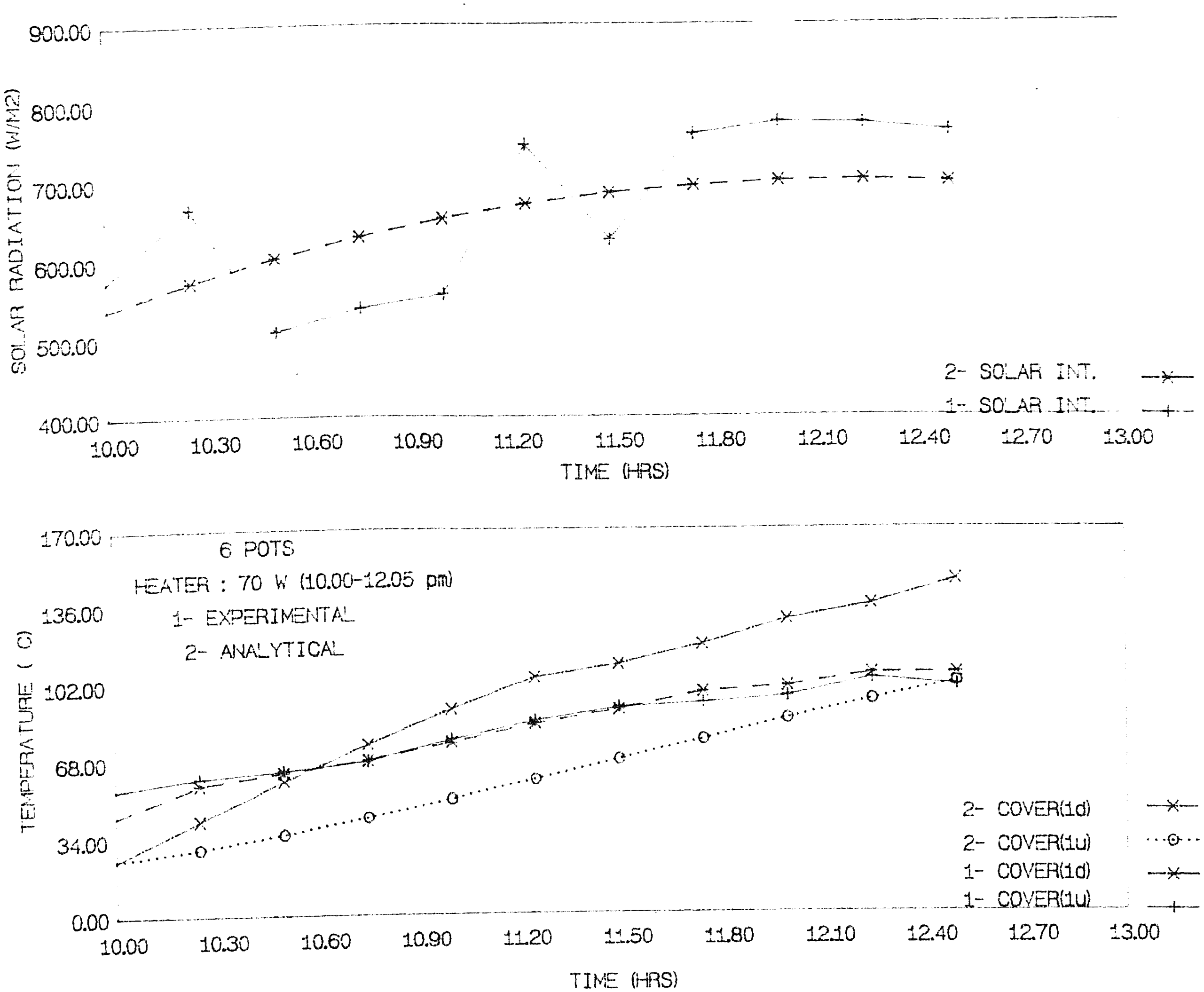


Fig. 6.17 Comparison of computational and experimental results (Heater 70 W)

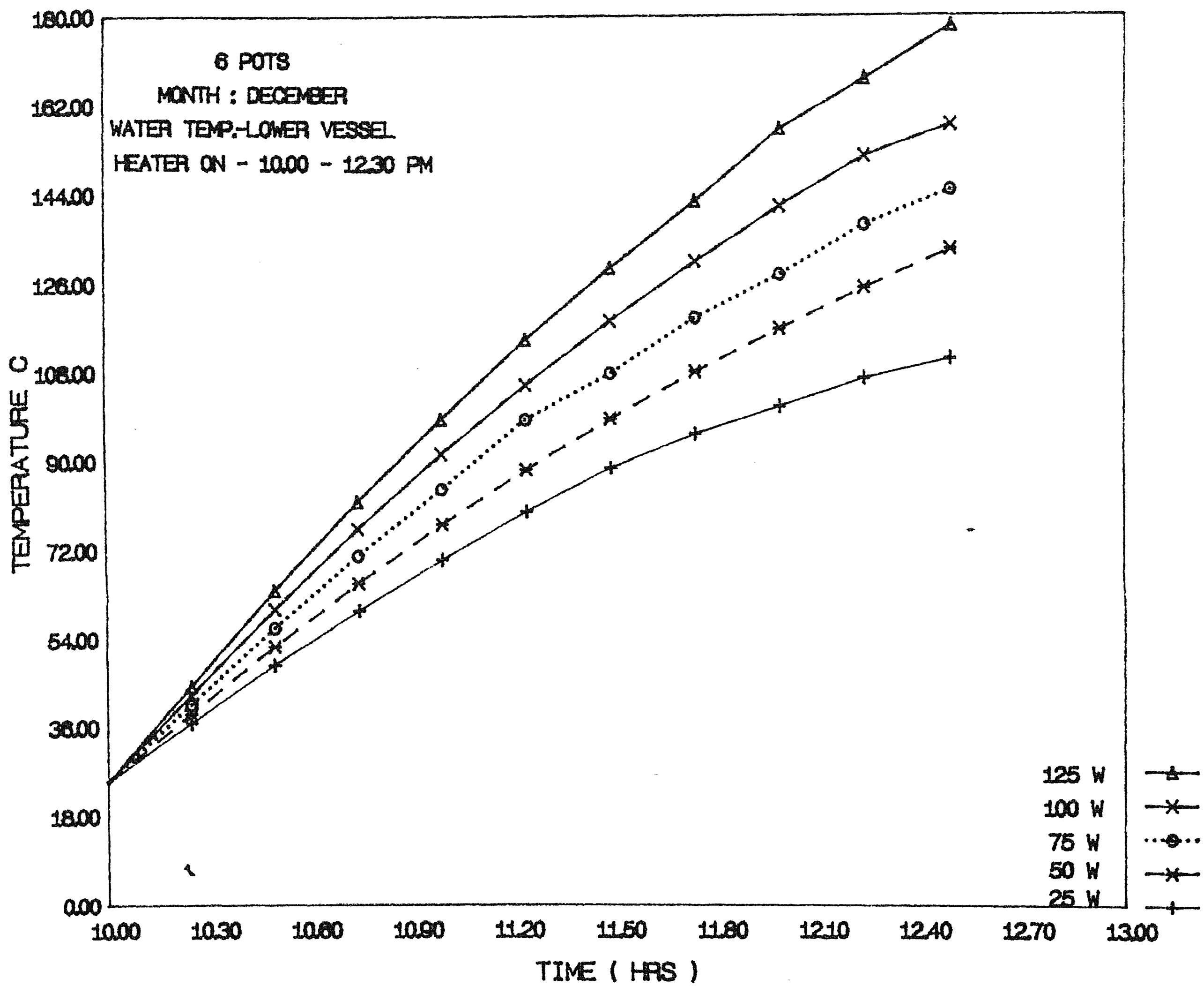


Fig. 6.18 Variation of water temperature with time in lower vessel
(Heater 125, 100, 75, 50, 25 W)

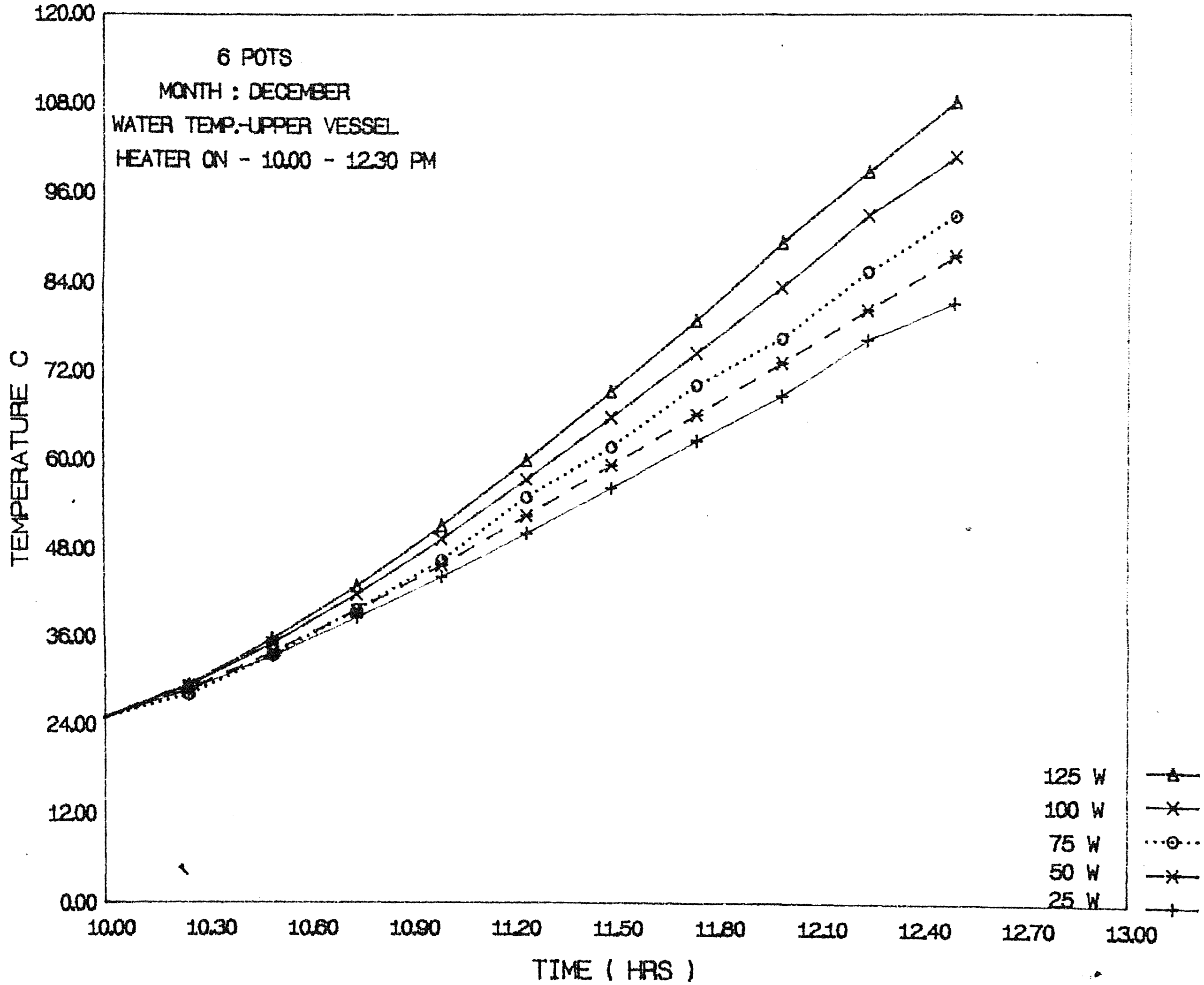


Fig. 6.19 Variation of water temperature with time in upper vessel (Heater 125, 100, 75, 50, 25 W)

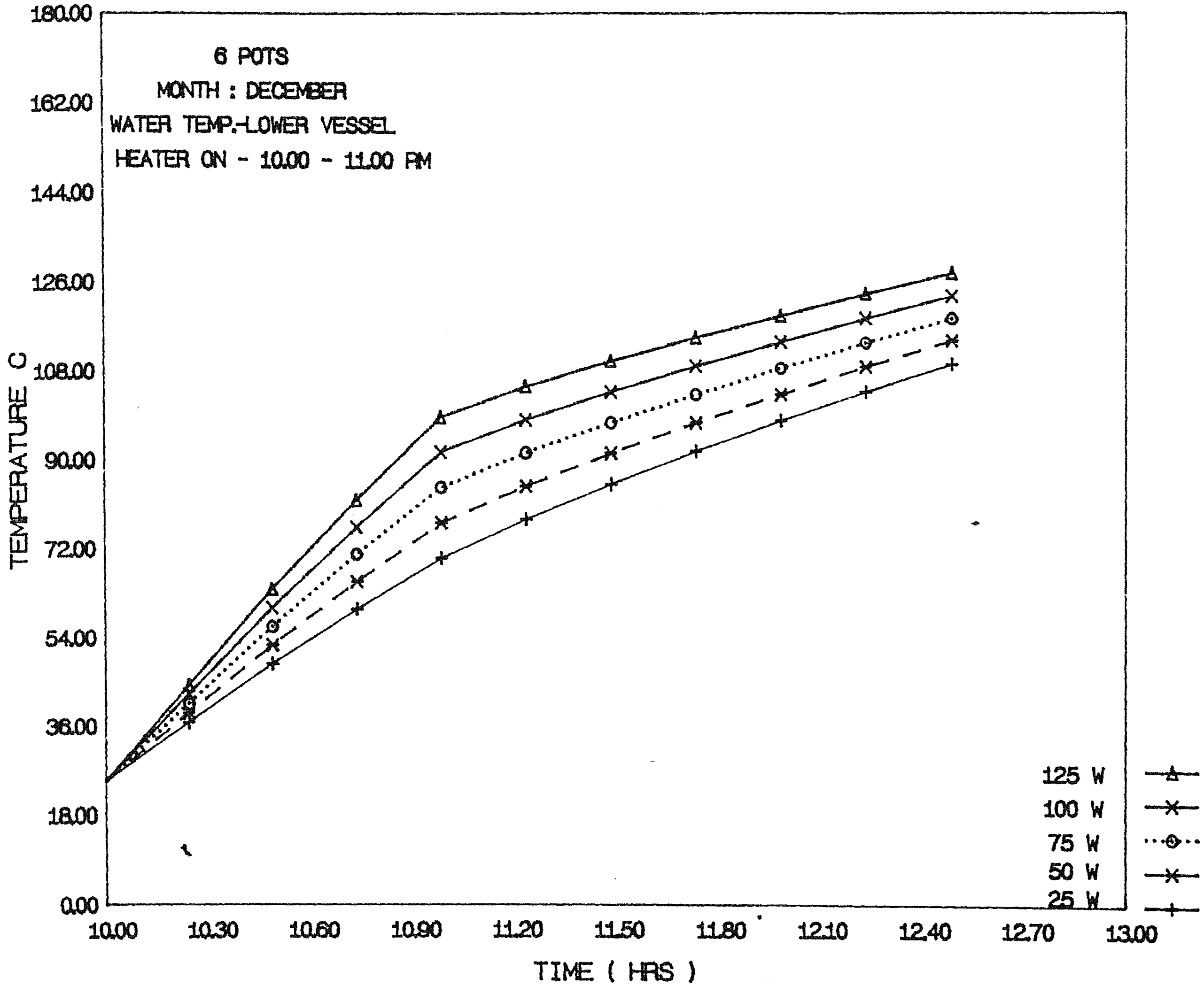


Fig. 6.20 Variation of water temperature with time in lower vessel
(1 Hour, Heater 125, 100, 75, 50, 25 W)

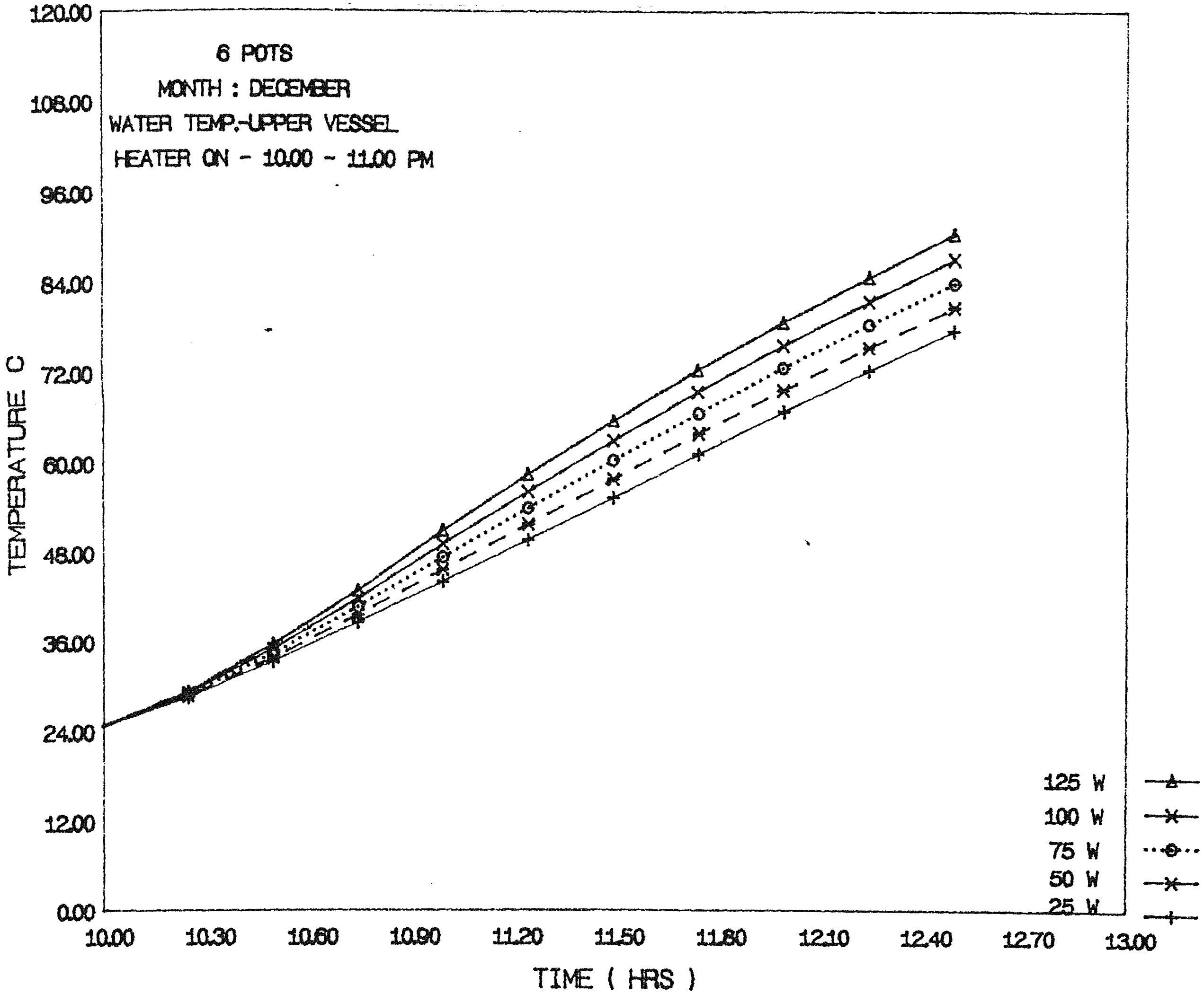


Fig. 6.21 Variation of water temperature with time in upper vessel
Heater 125, 100, 75, 50, 25 W)

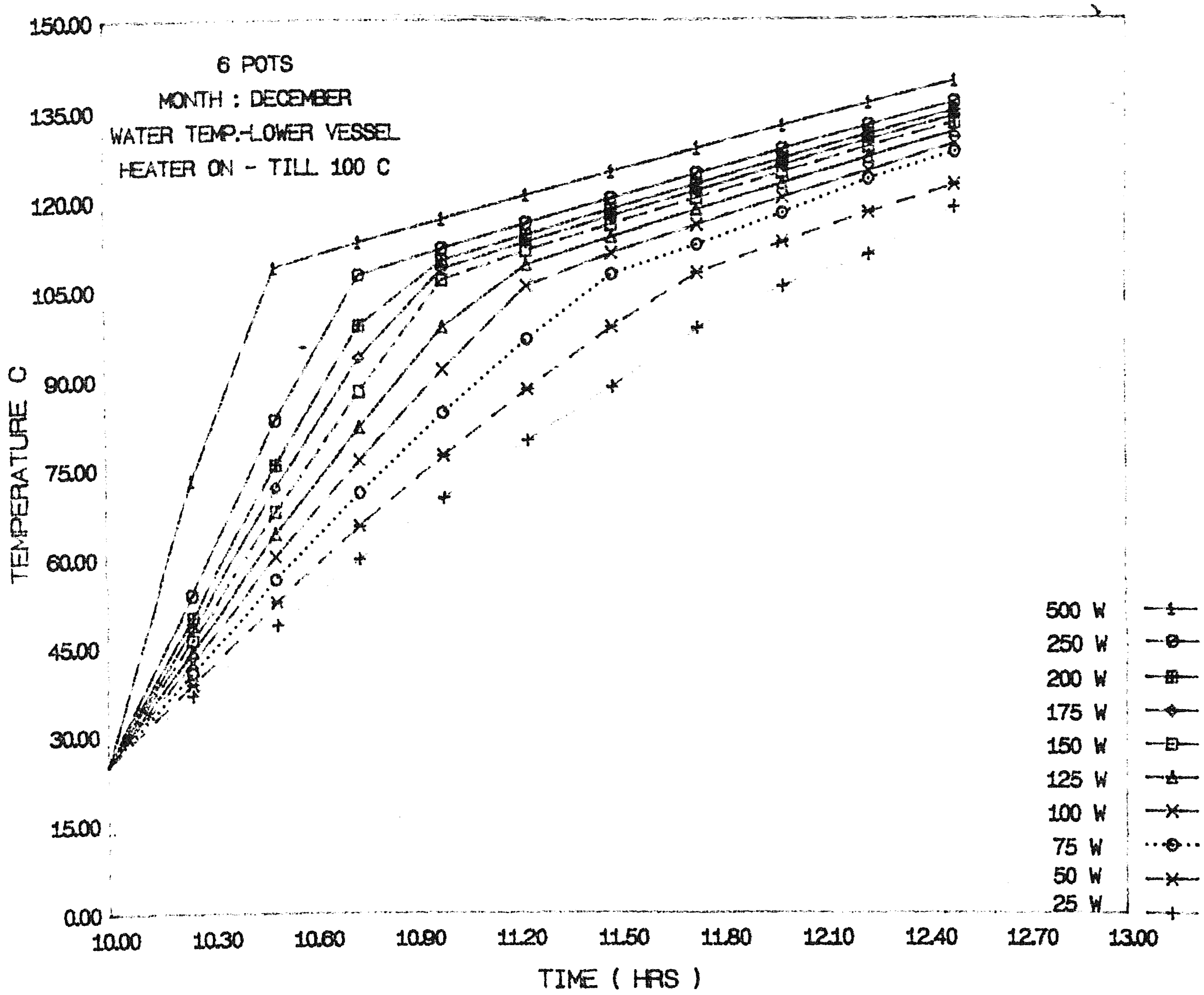


Fig. 6.22 Variation of water temperature with time in lower vessel (100 °C, Heater 500 - 25 W)

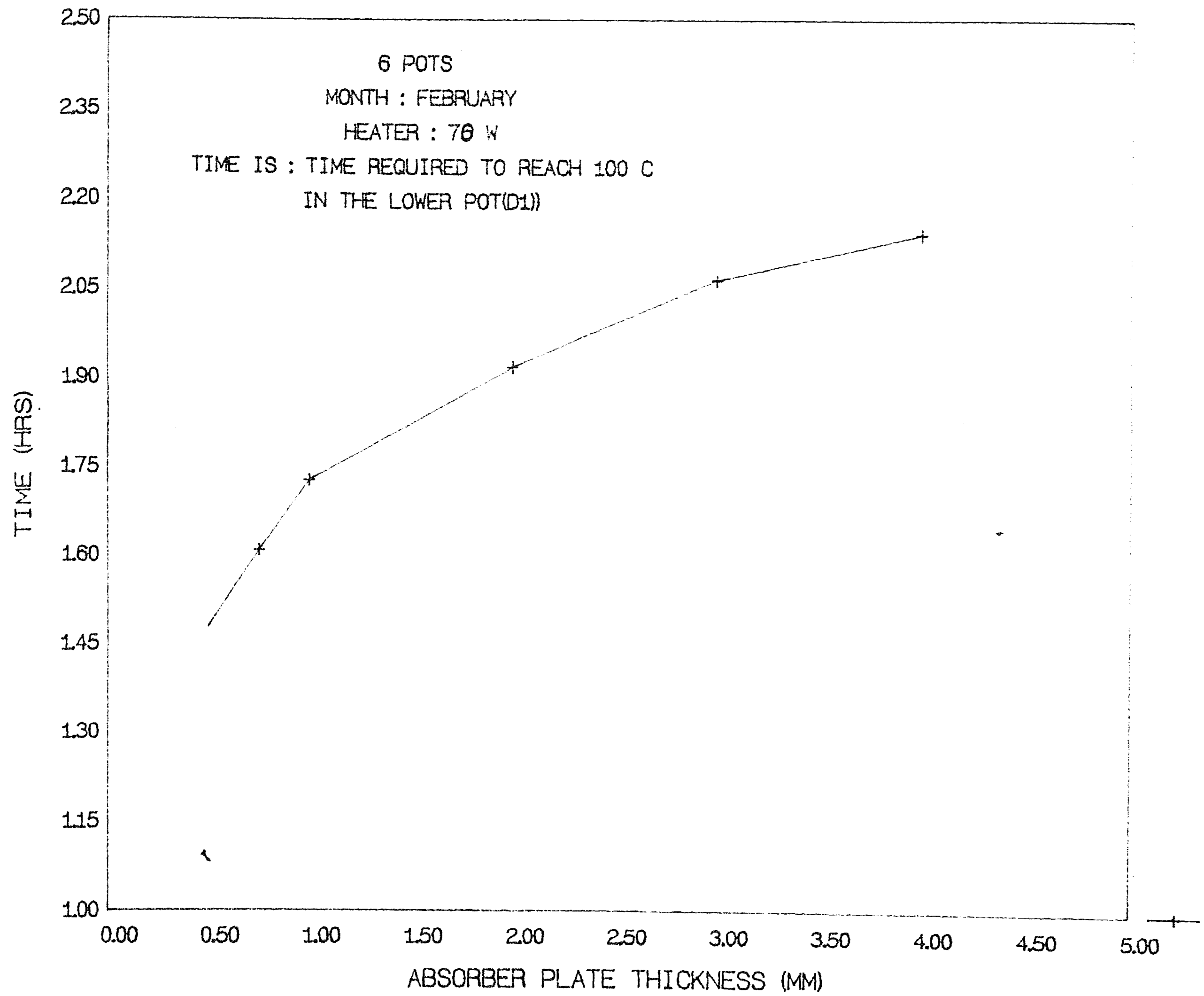


Fig. 6.23 Variation of time required to reach 100°C with absorber plate thickness

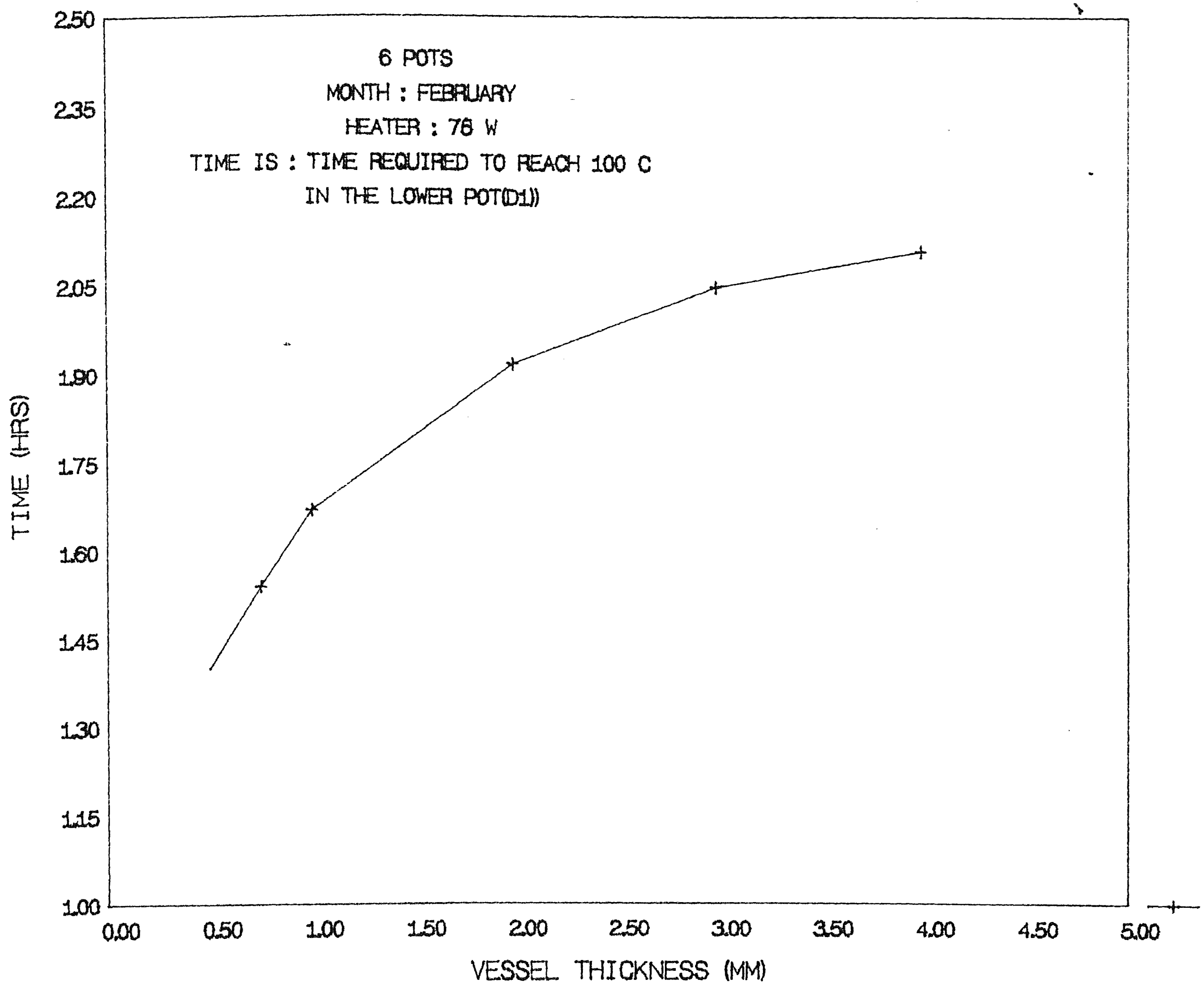


Fig. 6.24 Variation of time required to reach 100 °C with vessel thickness

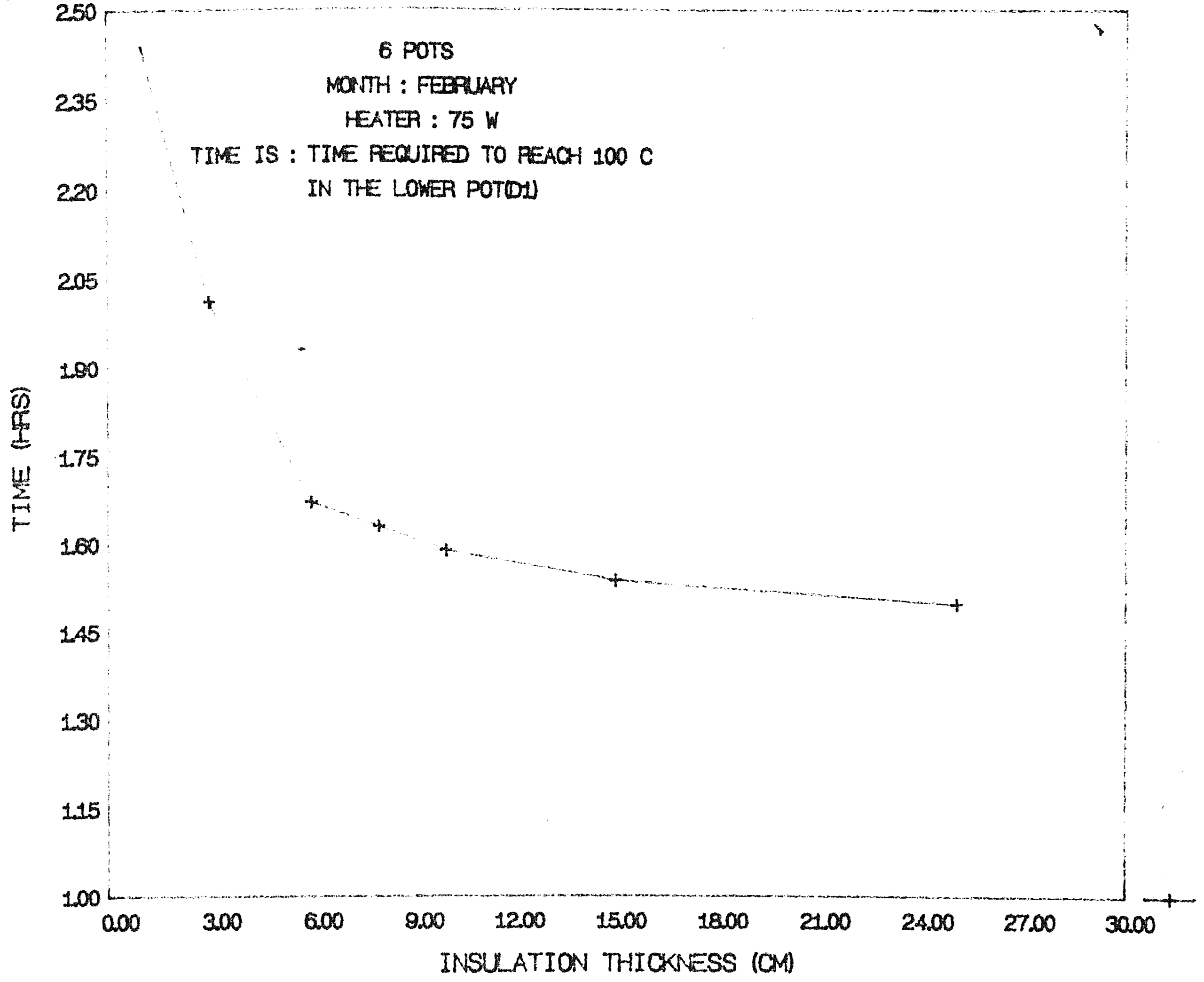


Fig. 6.25 Variation of time required to reach $100^{\circ}C$ with insulation thickness

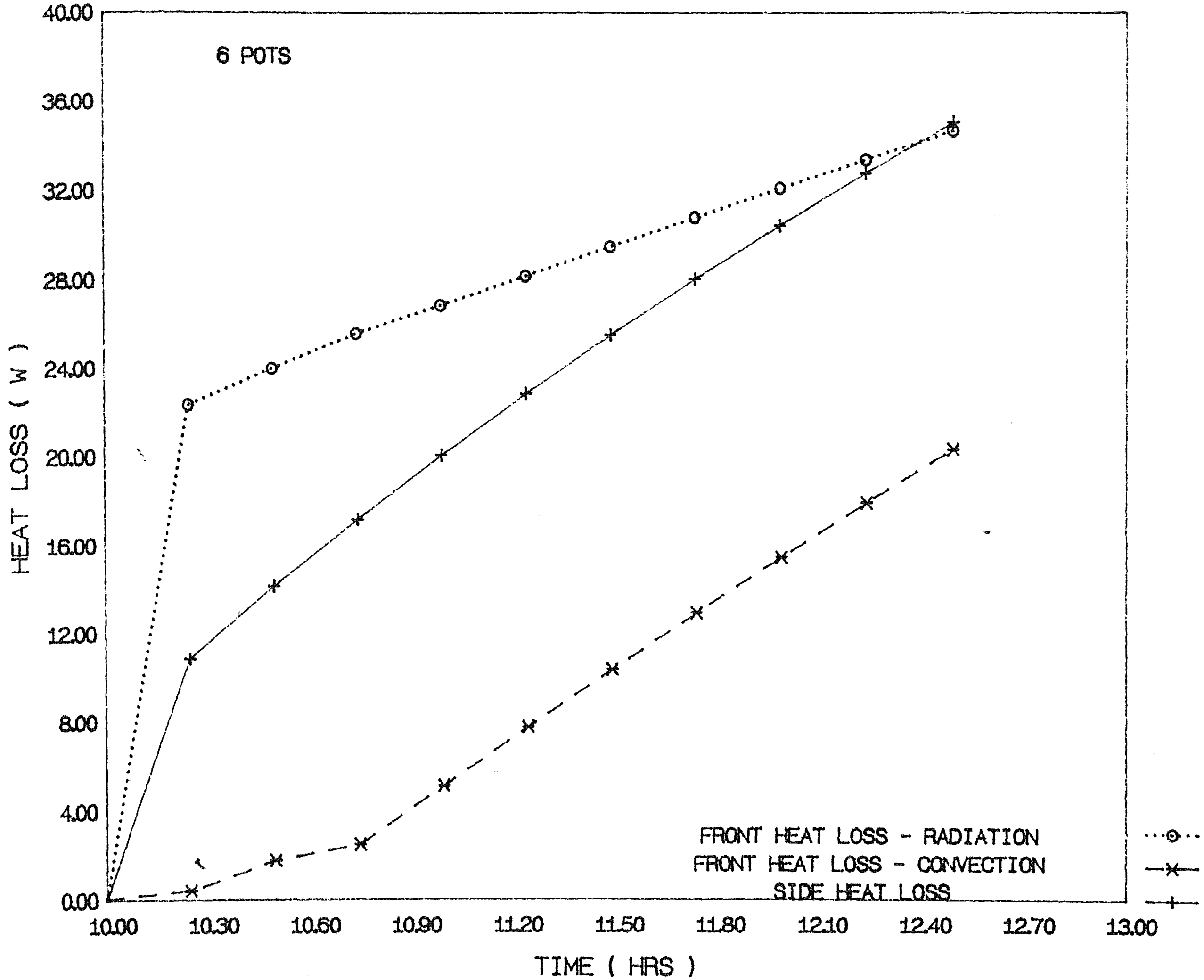


Fig. 6.26 Variation of heat loss with time

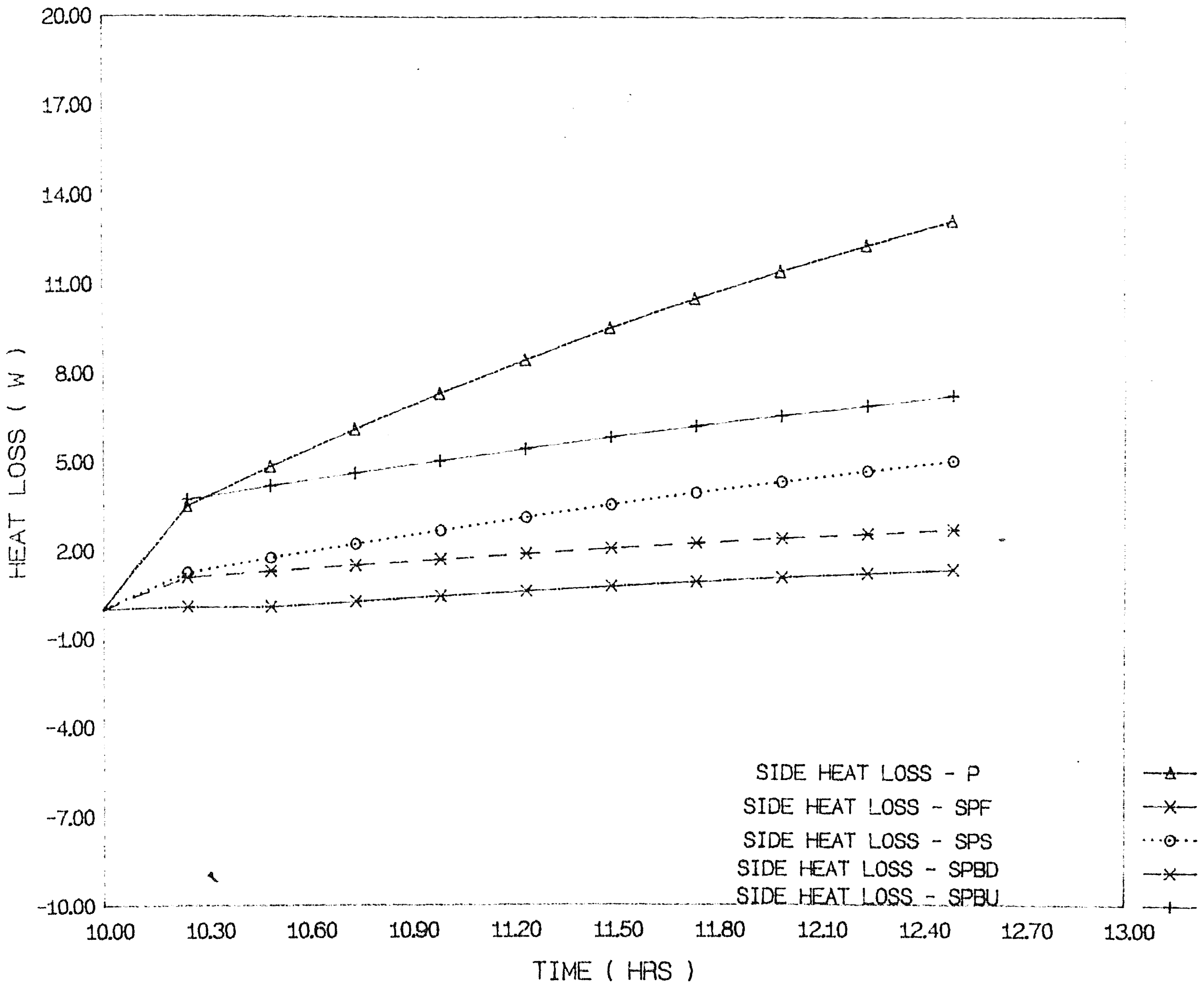


Fig. 6.27 Variation of side heat loss with time

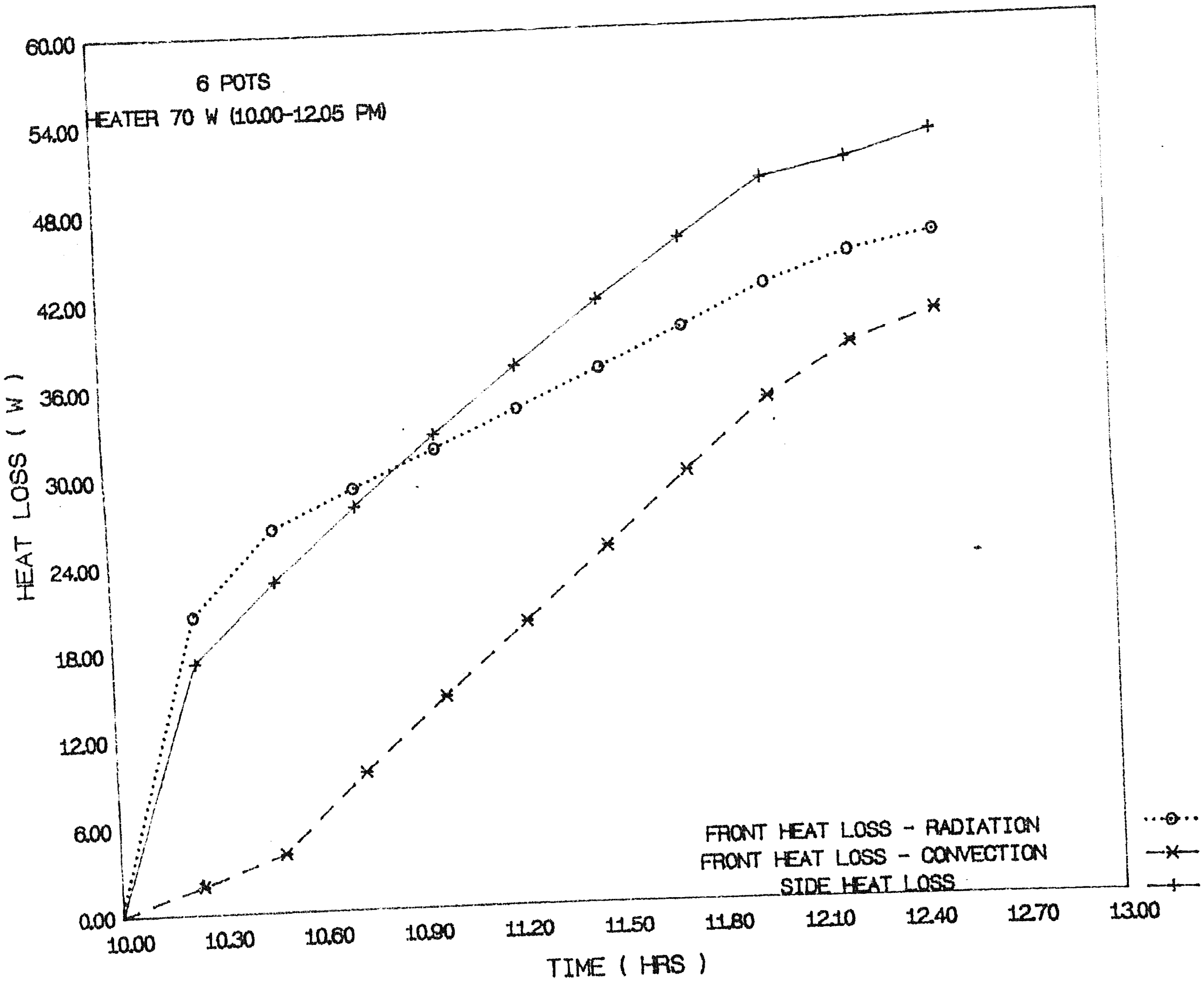


Fig. 6.28 Variation of heat loss with time (Heater 75 W)

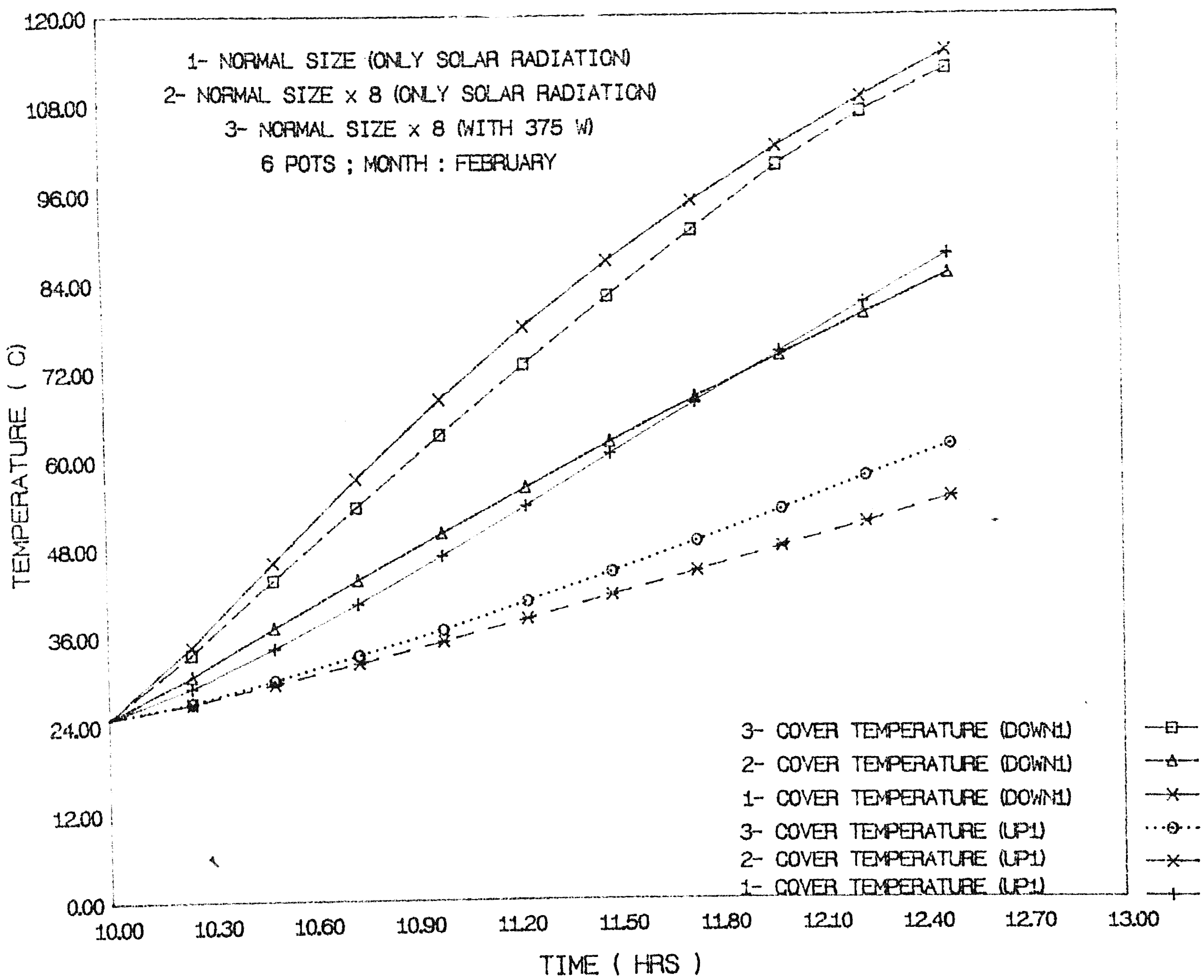


Fig. 6.29 Variation of vessel temperature with time
(Normal size x 8, Heater 375 W)

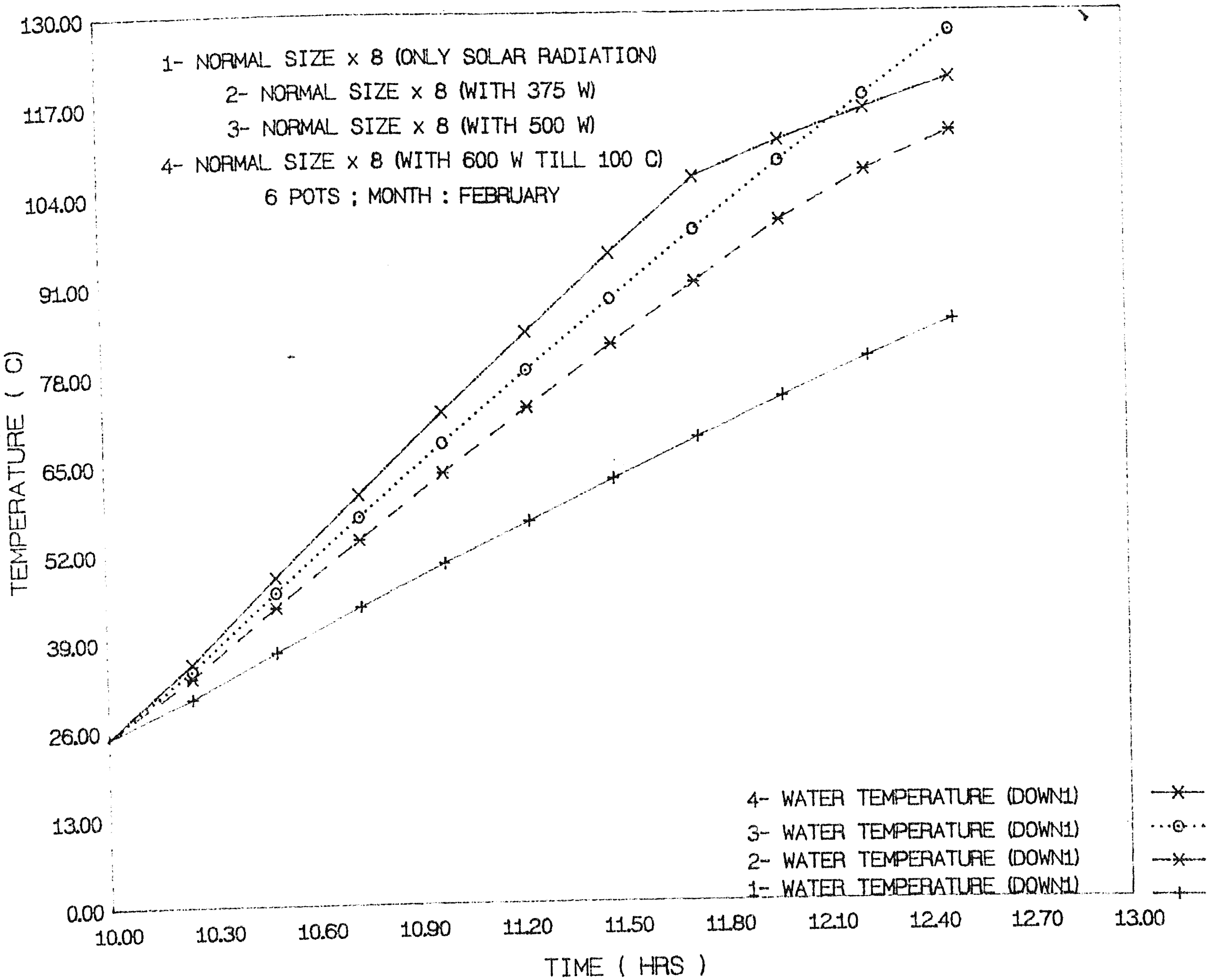


Fig. 6.30 Variation of vessel temperatures with time
(Normal size × 8, Heater 375, 500, 600 W)

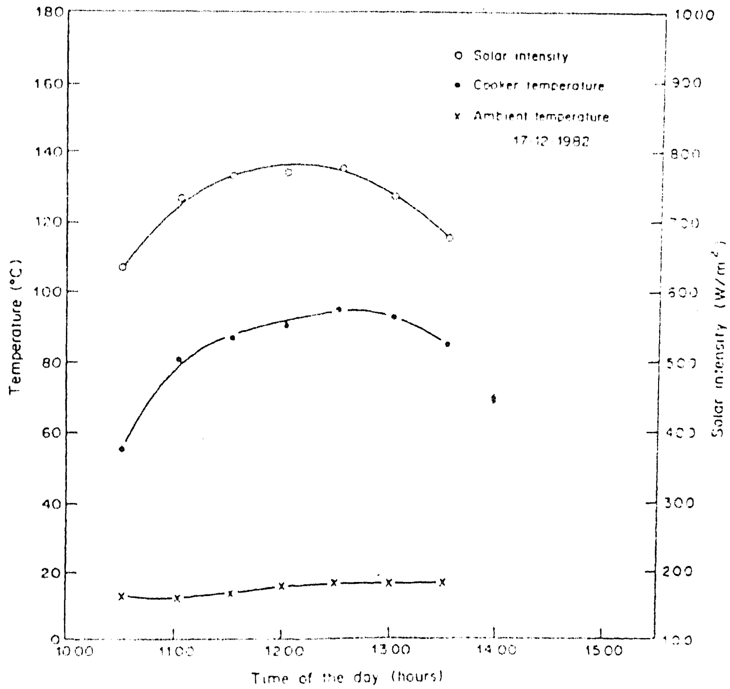


Fig. 6.31 Variation of the inside temperature of an empty solar cooker with global solar intensity and time of **day** **(Box-type solar cooker)**

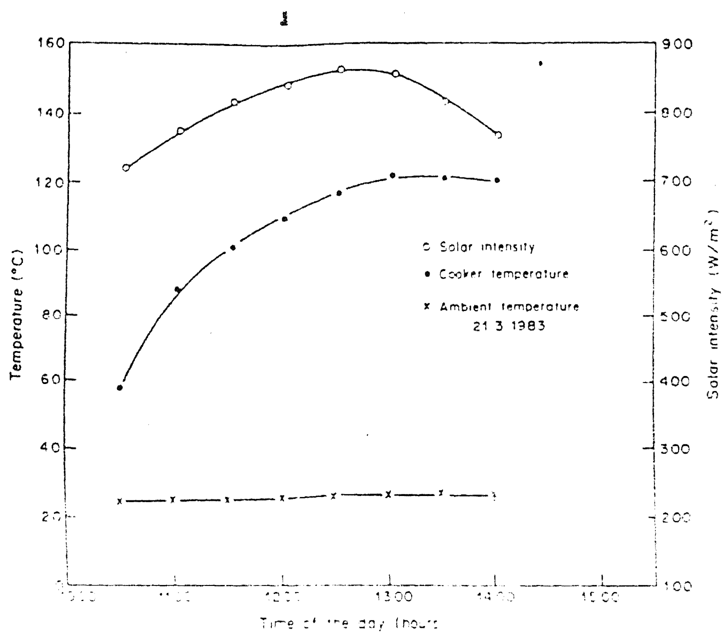


Fig. 6.32 Variation of the inside temperature of an empty solar cooker with global solar intensity andtime of **day** **(Box-type solar cooker)**

CHAPTER 7

CONCLUSIONS AND SUGGESTIONS

7.1 CONCLUSIONS :

A new design for the solar cooker is presented. The concept of hybridization is incorporated in it. Experimental and computational investigations have been carried out in order to evaluate the performance of the cooker and at the same time to compare the computational results with the experimental results and to study the factors which affects its design and performance:

The experiments and the computational investigation confirmed the validity and success of inclusion of certain new features in the design. At the same time this investigation offers the scope of improvement of certain design features of the cooker:

1. Inclusion of tilted collector has resulted in the enhancement of the collected solar energy.
2. Handling of the vessels has become very easy due to the placement of the door at the back of the cooker.
3. Removal of the glass reflector has resulted in easy handling and less weight and cost of the cooker.
4. As the tracking of the cooker is not required, no attention during the cooking is needed.
5. There are possibilities of using the big sizes of this new design with the inclusion of biogas for the purpose of community cooking in both urban and rural areas.

6. The provision of the door at the back of the cooker dispenses with lifting of the glass cover. Hence the possibility of its breakage is eliminated. Moreover this new position of the door results in less heat loss from the cooker whenever the heated cooker is opened.
7. The cooker has become more leak proof due to fixed glass cover.
8. With the expenditure of little supplementary energy food can be cooked easily even in the winter months. About 150 W of supplementary energy rate for 1.30 h with 600 W/m^2 of global solar radiation can heat 2.4 kg water up to 100 $^{\circ}C$.
9. Reduction of thermal load does not results in the increase of energy collection in the same proportion due to large heat loss area.
10. Upper vessels receives less energy. Hence some change in the design is necessary to increase the heat transfer to the pots on the grill.
11. Temperature profiles obtained by the computer simulation shows the same trends as obtained by the experimental data. Hence the mathematical model can be used to predict many design features of the new cooker.

7.2 SUGGESTIONS FOR THE FUTURE WORK :

The basic aim of the present study was to initiate the experimental and computational work on the new design. Within the time available it was not possible to analyze the collected data

completely. Hence work needs to be done in this area.

More experiments need to be performed on the different sizes this new design to see the effect of supplementary energy supply rate, amount of thermal load, inclusion of reflector and tracking etc. An extensive mathematical model has been developed. To simulate it, a lengthy computer code has been written which can be used to compare different heat transfer rates within the cooker. Effect of these heat transfer rates on different design features needs to be investigated. In the present study this part is not included. This code can be made more general by including in it provision for different number of glazings in the cover system, different number and arrangement of vessels etc.

On the basis of the present study a new design is proposed which can be used as the basis for starting further research on this topic (fig. 7.1).

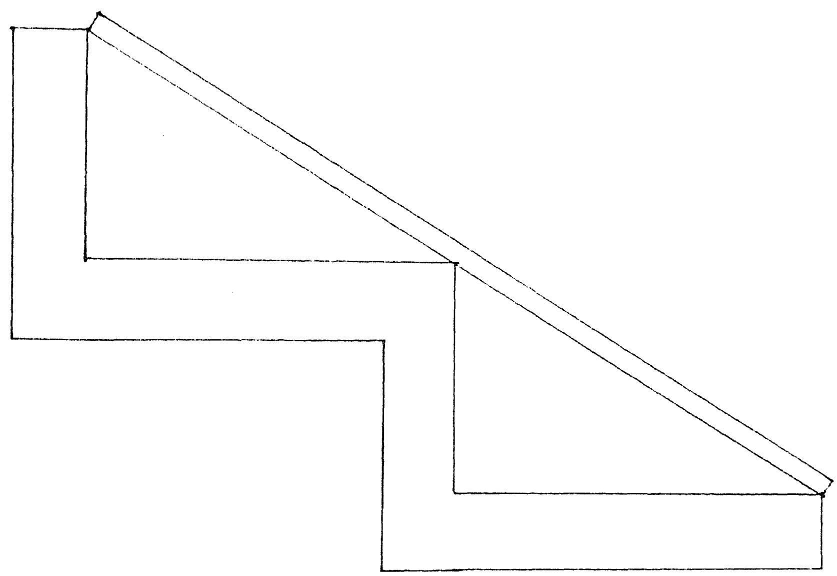


Fig. 7.1 Schematic diagram of the proposed design.

REFERENCES

1. Garg, H.P., Mann, H.S., Thanvi, K.P., "Performance Evaluation of Five Solar Cookers", Sun - Mankind's Future Source of Energy, *Proc.of the Int. Solar Energy Society Congress*, New Delhi, India, V-3, pp 1491 - 1496, 1978.
2. Hoda, M. M., "Solar Cookers", Sun - Mankind's Future Source of Energy, *Proc.of the Int. Solar Energy Society Congress*, New Delhi, India, V-3, pp 2065 - 2070, 1978.
3. Gosh, M. K., "An Approach to a Self Sufficient Domestic Solar Energy Units", Sun - Mankind's Future Source of Energy, *Proc.of the Int. Solar Energy Society Congress*, New Delhi, India, V-3, pp 2165 - 2166, 1978.
4. Osman, M. G., "Solar Energy for Cooking in Egypt", Sun - Mankind's Future Source of Energy, *Proc. of the Int. Solar Energy Society Congress*, New Delhi, India, V-4, pp 1768 - 1695, 1978.
5. Khalifa, A. M. A., Taha, M. M. A. and Akyurt, M., "Solar Cookers for Outdoors and Indoors", *Energy*, Vol. 10 No.7, pp 819 - 829, 1985.
6. Tiwari, G. N. and Yadav, Y. P., "A New Solar Cooker Design", *Energy*, Vol. 26 ,No.1, pp 41- 42, 1986.
7. Pande, P. C. and Thanvi, K. P.,"Design and Development of a Solar Cookers for Maximum Energy Capture in Stationary Mode", *Energy Conv. Mgmt.*, Vol. 27, No.1, pp 117 - 120, 1987.
8. Khalifa, A. M. A., Taha, M. M. A. and Akyurut, M., "Design, Simulation and Testing of a New cocentrating Type Solar

Cookers", *Solar Energy*, Vol. 38, No. 2, pp 75 - 88, 1987.

9. Grupp, M., Montagne, P. and Wackernagel M.,"A Novel Advanced Box Type Solar Cooker", *Solar Energy*, Vol. 47, No. 2, pp 103 - 113, 1991.

10. Olwi, I. and Khalifa A., "Numerical Modelling and Experimental Testing of a Solar Grill", *Journal of Solar Energy Enginnering*, Vol. 115 , pp 5 - 10, 1993.

11. Hall A., Swet C. J. and Temanson L. A.,"Cooking With Stored Solar Heat", Sun - Mankind's Future Source of Energy, *Proc. of the Int. Solar Energy Society Congress*, New Delhi, India, V-1, pp 547 - 553 , 1978.

12. Farber, E. A., Ingley, H. A. and Morrison C.A.,"The Design and Evaluation of a Hydraulc-Solar Powered Tracking Device", Sun - Mankind's Future Source of Energy, *Proc. of the Int. Solar Energy Society Congress*, New Delhi, India, V-2, pp 1341 - 1346, 1978.

13. Buxey, D., "Solar Cookers", Solar Energy Int. Progress, *Proc. Of the Int. Symposium Workshop on Solar Energy*, Egypt, Vol 4 pp 1766 - 1767, 1978.

14. Walten, J. D. Jr. and Bomer, S. H., "Solar Energy Applied to the Needs of Sub Sahara Africa", Sun II, *Proc. of the Int. Solar Energy Society Congress*, Atlanta, Georgia, V-2, pp 1465, 1979.

15. Nahar, N. M. and Gupta, J. P., "Energy Conservation Potential for Solar Cookers in Arid Zones of India", *Energy*, Vol.16, No.6, pp 965- 969, 1991.

16. Kammen, M.and Lankford, W.M., "Cooking in the Sunshine", *Nature*, Vol. 358.29, pp 385- 386, 1990.

17. Khandpal, T. C. and mathur, S. S., "The Economics of the Box Type Solar Cookers", *Energy Conv. Mgmt.*,Vol. 26 ,No.2, pp 233 – 235, 1986.

18. Malhotra, K. S., Nahar, N. M. and Ramana Rao, B. V., "Optimization Factor of the Solar Ovens",*Solar Energy,* Vol. 31, No.2, pp 235 – 237, 1983.

19. Vashya, J. S., Tripathi, T. C., Singh, D., Bhawalkar,R. H. and Hegde, M. S. ,"A hot box Solar Cooker: Performance Analysis and Testing", *Energy Conv. Mgmt.*, Vol. 25, No.3, pp 373 – 379, 1985.

20. Dang, A., "An Analytical Study of Solar Cookers Augmented with a Booter Mirror Using PCM as a Storage", *Energy Conv. Mgmt.*,Vol. 25 No.3, pp 255 – 261, 1985.

21. Mullick, S. C. Kandpal, T. C. and Saxena, A. K., "Themal Test Procedure for Box Type Solar Cookers", *Solar Energy*, Vol. 39, No.4 pp 353 – 360, 1987.

22. Yadav, Y. P. and Tiwari, G. N., "Transient Analitacal Study of Box Type Solar Cooker", *Energy Conv. Mgmt.*,Vol. 27, No.2, pp 121 – 125, 1987.

23.Olwi, I. A. and Khalifa , A. M. A., "Computer Simulation of Pressure Testing of a New cocentrating Type Solar Cookers", *Solar Energy*, Vol. 38, No. 2, pp 78 – 88, 1987.

24. Channiwala, S. A. and Doshi, N. I., "Heat Loss Coefficient for Box Type Solar Cookers", *Solar Energy*, Vol. 42, No. 6, pp 495 – 501, 1989.

25. Gururaja, J. and Ramchandan, A.,"Chracteristics of the Rural Energy Demand and Major Barriers and Tasks and Implementaion of Potentialy Viable Solar Technology", *Sun II Proc. of the*

Int. Solar Energy Society Congress, Atlanta, Georgia, V-2, pp 1466 - 1670, 1979.

26. Kreder and Kreith, "Agricultural and Other Low Temperature Applications of Solar Energy", Solar Energy Handbook, Mc-Graw Hill Company , 1981.

27. Guest Editoral, "Institutional and Financial Changes That Need to be Implemented to Bring Solar and Renewable Energy into Significanty Worldwide Markets", *Solar Energy* , Vol.50, No. 2, pp 101 - 103, 1993.

28. Vita, Solar Cooker Constructional Manual, Union College Campus, Schenectady, N. Y., U. S. A., 1967.

30. Taha, I. S. and Eldighidy, M. H., "Effect of Off South Orientation on Optimum Condition for Maximum Solar Energy Absorbed by Flat Plate Collector Augmented by Plane Reflector", *Solar Energy*, Vol. 25, pp 373 - 379, 1980.

31. Churchil, S. W. and Chu, H. H. S., "Correlating Equations for Laminar and Turbulent free Convection from a Vertical Plate", *Int. Jl.. of Heat Mass Transfer*, Vol. 18, pp 1323- 1329, 1975.

32. Kuan, D. Y., Asris, R., and Davis, H. T., "Estimation of Fin Efficiencies of regular Tube Arrayed in Cicumferencial Fins," *Int. j. of Heat Mass Transfer*, Vol. 27, No. 1 , pp148 - 151, 1984.

33. Villarrubia, M., Coronus, A. and Leorence, M., "Solar Radiation Incident on Tilted Flat Surfaces in Barcelona, Spain", *Solar Energy*, Vol. 25, pp 259- 263, 1980.

34. Dang, A. and Sharma, J. K., "Performence of Flat Plate Solar Collectors in Off South Orientation in India", *Energy Conv.*

and Mgmt., Vol. 23 No. 2 pp 125 - 130, 1983.

35. Hawas, M. M., and Muneer, T., "Study of Diffuse and Global Radiation Characteristics in India', *Energy Conv. and Mgmt.*, Vol. 24 No. 2 pp 143 - 149, 1984.

36. Muneer, T. Moutafa, M. , Hawas, M. and Shahali, K., "Correlation Between Hourly Diffuse and Global Radiation for New Delhi", *Energy Conv. and Mgmt.*, Vol. 24,No. 4 pp 265 - 267, 1984.

37. Saraf, G. R. and Hamad, F. A. W., "Optimum Tilt Angle for a Flat Plate Solar Collector', Energy Conv. and Mgmt., Vol. 28, No. 2, pp 185 - 191, 1988.

38. Garg, H. P. and Hrishikeshan, D. S., "Enhancement of Solar Energy on Flat Plate Collector By Plane Booster Mirrors", *Solar Energy*, Vol.40, No. 4, pp 295 - 307, 1988.

39. Narsihmha Rao, A. V., Rao, T. L. S. and Subramnayan, S., "Mirror Boosters for Solar Cookers - I", *Energy Conv. and Mgmt.*, Vol. 28No. 3 pp 265- 269, 1988.

40. Das, T. C., Karmarkar, S. and Rao, D. P., " Solar Box-Cooker -Modelling, analysis & Simulation, *Solar Energy*.(submitted).

41. Anderson , E. E., Fundamentals of Solar Energy Conversion, Adison-Wiley Publishing Company, 1983.

42. Shukhatme, S. P., Solar Energy Principles of Thermal Collection and Storage, Tata-McGraw Hill Publishing Company Ltd. 1984.

43. Reddy, T. A., The Design and Sizing of Active Solar Thermal Systems, Clarendon Press, 1987.

44. [illegible]

Company,1968.

45. ASHRAE, Handbook of Fundamentals, chapters 26,27, 1982.

46. Sparrow, E. M. and Coss, R. D., Radiation Heat Trnsfer, Mc-Graw Hill Book Company, 1978.

47. Eckert, E. R. G. and Drke, R. M., Analysis of Heat and Mass Transfer, Mc-Graw Hill Book Company, 1972.

48. Arora, S. C. and Domkundwar, S., A Course in Heat and Mass Transfer, Dhanpat Rai & Sons, 1990.49. Kreith, Frank,

49. Radiation Heat Transfer for Spacecraft and Solar Process Power Plant Design, International Textbook Company, 1962.

50. Hamilton, D. C., and Morgan, W. R., *Radiant Interchange Configuration Factors,* NACA, TN-2836, 1952.

51. Prasad,Manohar, Refrigeration and Airconditioning Data-Book, Wiley Eastern Limited, 1989.

52. Sarkar, H. and Kadekodi, G. K., Energy Pricing in India, International Labour Organisation Publication, 1987.

53. Sankar, T. L., India's Energy Policy (With Perspective upto 2000 A. D.).

54. Dekhane, M, Vohra, S., Kumar, A., "*Hybrid Solar Cooker*", B.Tech. Project Report, IIT Kanpur, 1990.

55. Threlkeld, J. L., Thermal Environmental Engineering, Prentice Hall, New Jeresy.

APPENDIX A

Several parameters have been mentioned in the main body of the text without the necessary equations or relationships being given to determine them. These are given below with a minimum of explanation since they involve well-established relationships found in many solar energy textbooks.

A.1 INTRODUCTION

The earth's mean distance to the sun is about 1.50×10^8 km (9.3×10^7 miles). Since the intensity of solar radiation incident upon the top of the atmosphere varies inversely with the square of the earth-sun distance, the earth receives approximately 7 % more radiation in December than in June. However, the fact that it is hotter in summer than in winter id due primarily to the near-normal solar incidence angles during the former time period.

The North Pole is inclined at an angle of 23.5° away from the sun. All points on the earth's surface above 66.5° north latitude are in total darkness while all regions within 23.5° of the South Pole receive continuous sunlight.

A.2 BASIC SUN-EARTH ANGLES:

The position of a point P on the earth's surface with

respect to the sun's rays is known at any instant if the latitude L, hour angle W for the point, and the sun's declination δ are known. These fundamental angles are shown in Fig. A.1. Point P represents a location in the northern hemisphere.

The *latitude* L is defined as the angular distance of the point P north (or south) of the equator.

The *hour angle* W is the angle measured in the earth's equatorial plane between the projection of OP and the projection of a line extending from the center of the earth. At solar noon, the hour angle is zero.

The *sun's inclination* δ is defined as the angular distance north (or south) of the equator of the point where the sun is at the zenith.

Because the period of the earth's complete revolution about the sun does not coincide exactly with a calendar year, the declination varies slightly on the same day from year to year.

A.3 SOLAR ANGLES:

Besides the three basic angles (latitude, hour angle, and declination), several other angles are useful in solar radiation calculations. These additional angles may be expressed in terms of the three basic angles (Fig. A.2).

(a) *zenith angle* θ_z is the angle between I_n and a line

[illegible]ndicular [illegible]

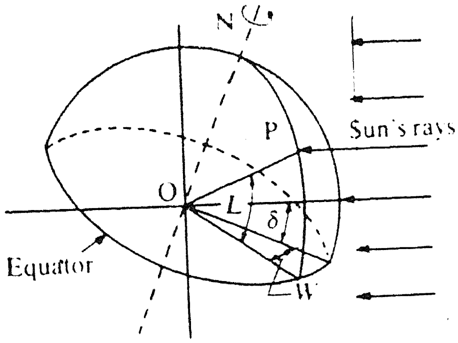
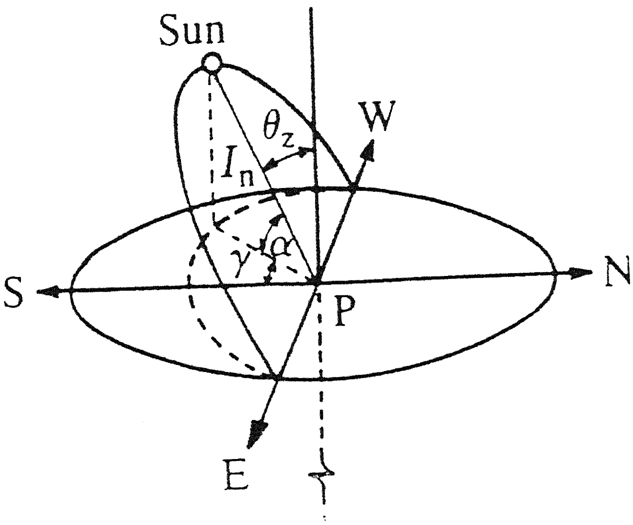


Fig. A.1 Latitude, hour angle, and sun's declination



Defini[illegible] angles

I_n and the projection of the sun's rays on the horizontal plane (it is evident that ($\alpha + \theta_Z = 90^\circ$).

(c) *azimuth angle* γ is the angle in the horizontal plane measured from the south to the horizontal projection of the sun's rays I_n. Eastwards from due south is taken as negative whereas westwards is positive.

The position of the sun in the sky is uniquely determined if the solar azimuth angle γ and the altitude angle α (or the zenith angle θ_z) are known.

A.4 ANGLES OF INCIDENCE:

For calculations involving other than horizontal surfaces, it may be convenient to express the sun's position relative to the surface in terms of the *incidence angle* θ. The orientation of the surface is determined with respect to two angles (Fig. A.3).

(a) the *slope angle* β, which is the angle that the surface makes with the horizontal plane; and

(b) the *azimuth angle* γ_p, which is the angle in a horizontal plane measured from due south to the horizontal projection of the normal to the surface.

$$\cos\theta = \sin\delta(\sin L\cos\beta - \cos L\sin\beta\cos\gamma_p) + \cos\delta\cos W(\cos L\cos\beta + \sin L\sin\beta\cos\gamma_p) + \cos\delta\sin\beta\sin\gamma_p\sin W.$$

If the tilt surface is equator-facing ($\gamma_p = 0$) this simplifies to

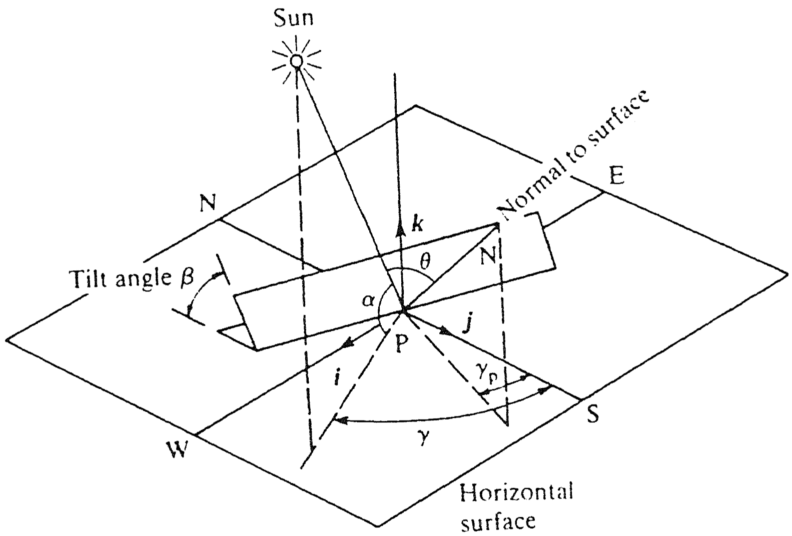


Fig. A.3 Relationships between the incident beam radiation and a tilted surface

APPENDIX B

The Free Convection Coefficients used in the calculations are reproduced here:

(a) *For Vertical Plates or Cylinders*

$$Nu_a = \frac{h_a L}{K} = 0.53\,(Gr\ Pr)^{1/4} \quad \text{for } Gr\ Pr < 10^5$$

$$Nu_a = \frac{h_a L}{K} = 0.56\,(Gr\ Pr)^{1/4} \quad \text{for } 10^5 < Gr\ Pr < 10^8$$

$$Nu_a = \frac{h_a L}{K} = 0.13\,(Gr\ Pr)^{1/4} \quad \text{for } 10^8 < Gr\ PR < 10^{12}$$

Characteristic length is the height of the plate or cylinder (L).

(b) Horizontal Square or Circular Plates

For horizontal hot surface facing upward or cold surface facing downward

$$Nu_a = \frac{h_a L}{K} = 0.71\,(Gr\ Pr)^{1/4} \quad \text{for } 10^3 < Gr\ Pr < 10^5$$

$$Nu_a = \frac{h_a L}{K} = 0.17\,(Gr\ Pr)^{1/3} \quad \text{for } Gr\ Pr > 10^9$$

For horizontal hot surface facing downward or cold surface facing upward

$$Nu_a = \frac{h_a L}{K} = 0.35\,(Gr\ Pr)^{1/4} \quad \text{for } 10^3 < Gr\ PR < 10^9$$

$$Nu_a = \frac{h_a L}{K} = 0.08\,(Gr\ Pr)^{1/3} \quad \text{for } Gr\ Pr < 10^9$$

the characteristic length is the side of the plate.

The above equations have been used as the pots are circular. The characteristic lenght for each case is the diameter of the pot.

APPENDIX C

The values of the constants A, B and C used for predicting hourly solar radiation on clear days are given in the table below

	A (W/m²)	B	C
January 21	1228	0.142	0.058
February 21	1213	0.144	0.060
March 21	1185	0.156	0.071
April 21	1134	0.180	0.097
May 21	1103	0.196	0.121
June 21	1087	0.205	0.134
July 21	1084	0.207	0.136
August 21	1106	0.201	0.122
September 21	1150	0.177	0.092
October 21	1191	0.160	0.073
November 21	1219	0.149	0.063
December 21	1232	0.142	0.057

*J.L. Threlkeld and R.C. Jordan, "Direct Solar Radiation Available on Clear Days", *ASHRAE Transactions*, 64, 45 (1958).

APPENDIX D

Parameters used for the simulation purposes

α_g = 0.025	α_p = 0.85	ε_g = 0.88
τ_g = 0.875	h_{ct} = 110 W/m^2 K	h_{cr} = 4 W/m^2 K
K_{ins} = 0.055 W/m K	K_{al} = 203 W/m K	h_{v-1} = 5 cm
h_{v-2} = 7 cm	d_{v-2} = 13 cm	d_{v-1} = 16 cm
$c_{p,w}$ = 4187 J/Kg K		